Numerical study on thermal management of battery based on PCM/micro-channel cooling

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Abstract. In recent years, the development of electric vehicles has made remarkable achievements. Its popularization and application can alleviate the problem of energy shortage and environmental pollution to some extent. In the process of discharging, the battery will generate heat. If the heat cannot be transferred to the external environment in time, the normal operation of the battery will be affected. In this paper, a BTM system based on PCM/micro-channel cooling is designed, and its cooling effect on battery module is studied by numerical simulation. The electrochemical-thermal coupling model is established to study the heat production and temperature changes of the battery during discharging. The cooling effect of the flow rate at the inlet of the cooling plate and the thickness of PCM on the battery module is studied. The results show that the BTM system can not only reduce the maximum temperature of the battery module, but also effectively improve the temperature inhomogeneity among the batteries.

1. Introduction

Due to the deterioration of environment and the shortage of energy, the traditional fuel car is no longer in line with the trend of the times. At the same time, the emergence of new energy vehicles, especially electric vehicles, can change this situation to a certain extent [1]. Owing to the characteristics of high energy density, high cycle times and no memory effect, lithium-ion battery has been widely used in various fields such as electric vehicles, notebook computers and digital cameras [2]. However, the battery will generate heat in the process of discharging. When the heat is accumulated to a certain degree, the temperature of the battery will be increased greatly, which will not only affect the normal use of the battery, but also cause danger. Therefore, it is necessary to propose an effective BTM system.

Under normal working temperature (20-40°C), lithium-ion battery has superior charging and discharging performance, which can meet the power demand of electric vehicles. In addition, in order to ensure good temperature uniformity of the battery module, the maximum temperature difference within the battery module should be less than 5°C [3-4]. Current thermal management schemes mainly include air cooling, liquid cooling and PCM cooling.
Air cooling is widely used in electric vehicles because of its simple structure and low cost. Wang, T [5] studied the forced convection air cooling scheme and found that the cooling effect of the battery module was the best when the fan was installed above the battery module. Lin, X [6] built the air cooling model of the battery pack in the simulation software ANSYS.

Liquid cooling is a cooling scheme that utilizes the high thermal conductivity of liquid to transfer the heat generated by the battery to the external environment in a timely manner. Cao, W.J [7] used the methods of experiment and simulation to study a full-size battery pack with micro-channel cooling system. Shah, K [8] established a steady convective cooling model for cylindrical lithium-ion batteries and found that increasing the radial thermal conductivity and axial convective heat transfer coefficient can significantly reduce the peak temperature.

PCM cooling is a relatively new cooling scheme. It mainly takes advantage of large latent heat of PCM, which can absorb heat and ensure the temperature of the battery in a reasonable range. Ouyang, D.X [9] studied the influence of battery spacing, SOC and PCM on the thermal runaway propagation of batteries. Yan, J.J [10] proposed a new sandwich structure, which was used to be a thermal barrier among batteries, including a heat conducting plate, a heat insulating plate and PCM.

In this paper, a BTM scheme based on PCM/micro-channel cooling is proposed, which can not only utilize high thermal conductivity of liquid cooling mode, but also take advantage of the characteristics of PCM with high latent heat of phase change. The tightly wrapped PCM absorbs the heat generated during discharging process, while the liquid cooling plate transmits the heat from the PCM to the external environment. The electrochemical-thermal coupling model is established to analyze the temperature variation of the battery during discharging. On this basis, the effects of liquid flow and PCM thickness on battery module’s temperature are discussed.

2. Model description

2.1. Electrochemical-thermal coupling model

In essence, the charging and discharging process of lithium-ion battery is the transportable process of lithium ion and electrons between the cathode and anode of the battery. Therefore, the law of mass conservation, the law of charge conservation and the law of energy conservation should be followed when the electrochemical model of lithium-ion battery is established. Cell is the basic structure of the battery, realizing charging and discharging function, which includes cathode, anode, separator, cathode collectors and anode collectors. It can completely express electrochemical-thermal effect in the process of charging and discharging, and simplify the calculation process. So a one-dimensional electrochemical model is established.

Mass conservation equation of lithium ion in solid phase can be expressed as

\[ \frac{\partial c_s}{\partial t} = \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 D_s \frac{\partial c_s}{\partial r} \right) \]  

(1)

Mass conservation equation of lithium ion in liquid phase can be expressed as

\[ \varepsilon_e \frac{\partial c_e}{\partial t} = \frac{\partial}{\partial x} \left( D_e^{\text{eff}} \frac{\partial c_e}{\partial x} \right) + \frac{\left( 1 - \varepsilon^0 \right)}{F} j \]  

(2)

Charge conservation equation in solid phase can be expressed as

\[ \frac{\partial}{\partial x} \left( \sigma^{\text{eff}} \frac{\partial \phi_s}{\partial x} \right) = aFj \]  

(3)

Charge conservation equation in liquid phase can be expressed as

\[ \frac{\partial}{\partial x} \left( \kappa^{\text{eff}} \frac{\partial \phi_e}{\partial x} \right) + \frac{\partial}{\partial x} \left( \kappa^{\text{eff}} \frac{\partial \ln c_e}{\partial x} \right) + j = 0 \]  

(4)

Energy conservation equation can be expressed as
\[ \rho C_p \frac{dT}{dt} = \nabla \cdot (\lambda \nabla T) + Q_e + Q_i \]  \hspace{1cm} (5)

2.2. PCM heat transfer model

The phase change process can be divided into three stages: solid phase, solid-liquid mixed phase and liquid phase. Among them, since solid and liquid phases exist in the second stage at the same time, the physical property parameters are related to the melting degree of PCM.

The density of PCM in the whole phase change process can be expressed as

\[ \rho = \rho_{PCMS} \quad (T < T_1) \]  \hspace{1cm} (6)
\[ \rho = \theta \rho_{PCMS} + (1-\theta) \rho_{PCML} \quad (T_1 \leq T \leq T_2) \]  \hspace{1cm} (7)
\[ \rho = \rho_{PCML} \quad (T > T_2) \]  \hspace{1cm} (8)

The specific heat capacity of PCM in the whole phase change process can be expressed as

\[ C_p = C_{p-PCMS} \quad (T < T_1) \]  \hspace{1cm} (9)
\[ C_p = \frac{1}{\rho} \left( \theta \rho_{PCMS} C_{p-PCMS} + (1-\theta) \rho_{PCML} C_{p-PCML} \right) + L_{PCM} \frac{\partial \alpha_p}{\partial T} \quad (T_1 \leq T \leq T_2) \]  \hspace{1cm} (10)
\[ C_p = C_{p-PCML} \quad (T > T_2) \]  \hspace{1cm} (11)

2.3. Liquid heat transfer model

The energy conservation equation of coolant in the cooling plate can be expressed as

\[ \frac{\partial}{\partial \tau} \left( \rho_w c_w T_w \right) + \nabla \cdot \left( \rho_w c_w \bar{v}T_w \right) = -\nabla \cdot (\lambda_w \nabla T_w) \]  \hspace{1cm} (12)

Momentum conservation equation of coolant can be expressed as

\[ \frac{\partial}{\partial \tau} \left( \rho_w \bar{v} \right) + \nabla \cdot \left( \rho_w \bar{v} \bar{v} \right) = -\nabla P \]  \hspace{1cm} (13)

The mass conservation equation of coolant can be expressed as

\[ \frac{\partial \rho_w}{\partial \tau} + \nabla \cdot \left( \rho_w \bar{v} \right) = 0 \]  \hspace{1cm} (14)

2.4. The geometric model

The established battery model is NCM battery, and the cathode material is Li(NiCoMn)O\(_2\), and the anode material is graphite. The battery is discharged from 4.2 V to 2.75 V. Four identical batteries are arranged, and the discharge process of each battery is similar. The battery cooling model is shown in Figure 1. Four single batteries are embedded in the PCM, and liquid cooling plates are installed on both sides of the PCM. The cross-section of the cooling channel is shown in Figure 2. PCM is graphite.
3. Result and discussions

3.1. Thermal characteristics of battery module

The thermal safety of the battery module is associated with the maximum temperature of the battery module and maximum temperature difference among batteries.

Figure 3 shows the variation curve of the maximum temperature of the battery module under different discharge current conditions. Due to the different discharge current, the time required for the battery module to discharge to the cut-off voltage is also different. As can be seen from Figure 3, the temperature of the battery module increases gradually with the increase of discharge time. Moreover, the higher the current, the higher the temperature reached at the end of the discharge of the battery module. When the discharge current of the battery module is 2C, the maximum temperature of the battery module is about 29.5℃. When the discharge current of the battery module is 10C, the maximum temperature of the battery module is about 53℃, which is beyond the normal operating temperature range of the battery module. If this situation is not improved, the battery will not work normally.

![Figure 3. Maximum temperature under different discharge currents](image)

![Figure 4. Maximum temperature difference under different discharge currents](image)

Figure 4 shows the curve of the maximum temperature difference of the battery module under different discharge currents. When the discharge current of the battery module is 2C, the maximum temperature difference of the battery module is about 0.64℃. As the discharge current increases, the maximum temperature difference of the battery module increases. When the discharge current of the battery module is 10C, the maximum temperature difference of the battery module is about 4℃, which has affected the normal operation of the battery. From the above research, it is necessary to propose an effective BTM system.

3.2. Impact of flow

The battery discharge current is set to 10C to study the cooling effect of PCM/micro-channel cooling system. When the gap between the batteries is 1mm, the liquid flow rate at the inlet of the cooling plate is set to $1\times10^{-4}$kg/s, $3\times10^{-4}$kg/s, $5\times10^{-4}$kg/s, $8\times10^{-4}$kg/s, $1\times10^{-3}$kg/s, and $1.2\times10^{-3}$kg/s, respectively. And the effect of the flow rate on the battery module model is discussed.

The maximum temperature of the battery module under different flow rates is shown in Figure 5. As can be seen from Figure 5, the designed cooling system can effectively reduce the maximum temperature of the battery module. With the increase of the flow, the maximum temperature of the battery module decreases. When the flow rate increases from $1\times10^{-4}$kg/s to $1.2\times10^{-3}$kg/s, the temperature decreases by about 4.7℃. At this time, the maximum temperature of the battery module is lower than 40℃, which can meet the normal operation requirement of the battery module. The maximum temperature difference of the battery module under different flow rates is shown in Figure 6. As can be seen from Figure 6, the maximum temperature difference of the battery module decreases.
with the increase of the flow. When the flow rate increases from $1 \times 10^{-4}$ kg/s to $1.2 \times 10^{-3}$ kg/s, the temperature decreases by about 1°C. And the maximum temperature difference of the battery module at this time is only 3°C, which improves the uniformity of the battery module temperature.

3.3. The influence of PCM thickness

When the liquid flow rate in the liquid cooling plate is $1 \times 10^{-3}$ kg/s, the thickness of PCM between the batteries is set to 1mm, 2mm and 3mm, respectively. The cooling effect of PCM thickness on the battery model is studied.

The maximum temperature of the battery module with different PCM thicknesses is shown in Figure 7, and the maximum temperature difference is shown in Figure 8. It can be seen that increasing the thickness of PCM is not obvious for reducing the maximum temperature of the battery module, but it can significantly improve the temperature uniformity of the battery module. When the thickness of PCM is 3mm, the maximum temperature difference of the battery module has decreased to about 2.5°C, which can guarantee the normal operation of the battery module.

4. Conclusion

In this paper, the battery cooling model based on PCM/micro-channel cooling is established, and the influence of flow rate and PCM thickness on the cooling system is discussed by numerical method. It is found that micro-channel cooling can not only effectively reduce the maximum temperature of
battery module, but also reduce the maximum temperature difference among batteries. Although PCM does not perform well in reducing the maximum temperature of the battery module, it can effectively guarantee the temperature uniformity among the batteries. In summary, the PCM/micro-channel cooling system can not only reduce the maximum temperature of the battery module, but also improve the temperature uniformity among the batteries.

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