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COMPARATIVE STUDY ON COOLING SCHEMES OF LITHIUM-ION BATTERY PACKS FOR ELECTRIC VEHICLES

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ABSTRACT

Lithium-ion batteries of electric vehicles have shorter life and lower safety in high-temperature environment, and battery packs need to be cooled to ensure that they operate in a suitable temperature range. In this study, two different cooling schemes were compared. With the maximum temperature and maximum temperature difference of a battery pack as indices, the thermal characteristics of the battery pack at a high discharge rate were studied by conducting a CFD simulation under fin forced convection cooling and composite cooling (fin and phase change material). The results showed that the maximum temperature and maximum temperature difference of the battery pack at high discharge rates can be significantly reduced under fin forced convection cooling (at low air flow rates) and composite cooling. Under the composite cooling, the system is simpler, and the uniformity between the batteries is better.

Keywords: lithium-ion battery pack, thermal management, fin, phase change, forced convection

1. INTRODUCTION

With the global energy shortage and environmental problems becoming increasingly prominent, the development of low energy consumption and low pollution electric vehicles (EVs) has become a research hotspot in the automotive industry. Compared with conventional lead-acid batteries and nickel-hydrogen batteries, lithium-ion batteries (LIBs) have been widely used in portable electronic devices, such as mobile phones, cameras, and laptops, because of their high specific energy, high discharge voltage, low self-discharge rate, long cycle life, and no memory effect [1]. In addition, they are preferred for new-generation hybrid electric vehicles (HEVs) and EVs power sources [2]. However, during the actual operation of a battery pack, the excessive temperature and uneven temperature distribution due to charging or discharging are one of the important factors leading to battery failure. Therefore, battery pack thermal management is a key technology that needs to be developed for commercializing batteries intended for electric vehicles.

Generally, the optimum operating temperature range of LIBs is 20–45 ℃, and the maximum temperature difference in the battery cell should be less than 5 ℃ [3]. Currently, heat dissipation methods for battery packs mainly include air cooling, liquid cooling, and phase change material (PCM) cooling. The air-cooling method has a simple structure and is cost-effective; however, the air convection heat transfer coefficient is low, thus significantly limiting its application to battery thermal management systems. Chen and Evans [4] argued that neither passive nor active air cooling can effectively dissipate the heat generated by large-scale batteries. Wu et al. [5] verified that under extreme conditions, particularly at high discharge rates and high operating temperatures (greater than 40 ℃), air cooling can not meet the temperature control requirements of battery pack operation. Compared with air cooling, liquid cooling has a higher convective heat transfer coefficient. Therefore, a battery pack can be effectively cooled, and a uniform temperature distribution between the batteries can be further achieved. Both Ford and Tesla vehicles use a mixture of water and alcohol as a coolant for cooling

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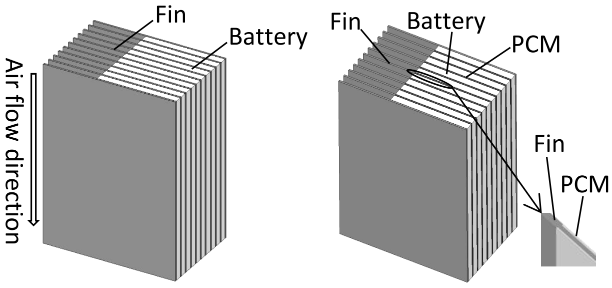
[6]. The main factor restricting the development of liquid-cooling systems is the need for complex devices to ensure liquid flow in a confined space. In recent years, thermal management systems based on PCMs as heat dissipation media have received increasing attention [7]. The main advantage of such a system is that it is relatively simple, without requiring additional energy-consuming equipment. However, because of the poor thermal conductivity of PCMs, heat is easily accumulated, bringing a series of potential safety hazards such as overheating of the battery pack.

A comprehensive analysis on existing thermal management technologies shows that the conventional single-cooling method does not meet all the heat dissipation requirements of LIBs. Composite thermal management systems using two or more thermal management methods have been proposed to overcome the thermal safety problems of LIBs. In this paper, a fin-type cooling structure is proposed. A fin forced convection air cooling method and a composite cooling (fin and PCM) method were studied to meet the thermal management requirements of a battery pack under high current discharge.

2. NUMERICAL MODEL

2.1 Physical model

In this study, ANSYS was used for the numerical simulation. The influence of battery electrodes was neglected in the numerical calculation process. The battery pack was symmetric after simplifying the electrodes. Thus, semi-structural models were used for the studied battery pack thermal management systems in the calculation. Figure 1 shows the battery pack semi-structural models used in this study. The battery cell is a $LiFePO_4$ battery with a rated capacity of 22 Ah, and the dimensions are 7.8 mm × 180 mm × 204 mm. A composite PCM with a high thermal conductivity made of paraffin wax and expanded graphite is used. Table 1 lists the specific parameters. The fin is made of copper with a thickness of 2 mm and an extension length of 60 mm. In the fin forced convection cooling model, the gaps between adjacent fins are filled with air. And the air flows parallel to the fins from top to bottom. In the composite cooling model, the normal thickness of the fin is 2 mm. After the PCM with a thickness of 0.5 mm is separately filled on both sides of the fin, the thickness of the fin becomes 1 mm.



(a) (b)

Fig 1 Semi-structural models of the battery pack under different thermal management methods; (a) Case 1 fin forced convection cooling method, (b) Case 2 composite cooling (fin and PCM) method

Table 1 Thermophysical properties of battery and PCM

	Battery	PCM [8]
Density (kg m^{-3})	2122	789
Specific heat (J kg^{-1} K^{-1})	933	1980
Thermal conductivity (W m^{-1} K^{-1})	21(⊥) / 0.48(∥)[a]	16.6
Melting point (℃)	—	40
Latent heat (J kg^{-1})	—	185000

[a] The thermal conductivity of the battery is orthotropic. It is lower across the thickness of the battery (∥).

In the process of numerical calculation, it is assumed that the battery generates heat uniformly and that the thermal conductivity of the battery is anisotropic. Table 1 lists the battery properties. The interfaces between the battery and the fin, the battery and the PCM are set to coupled ones. The third boundary condition is employed for the fin part extending out of the battery, and the surface heat transfer coefficient is set to 5 $W/(m^2{\cdot}K)$. The adiabatic boundary condition is employed for the sides of two end fins.

2.2 Thermal model

During the charge/discharge process of LIBs, Joule heat, polarization heat, reaction heat, and side reaction heat are generated because of many factors including ion migration and electrochemical reaction [9]. The heat generation rate of the battery cell is affected by factors such as the operating current, internal resistance, and battery state of charge (SOC). To reduce the complexity of temperature field calculation, the battery cell is simplified as follows: (1) The materials inside the battery cell are uniform; (2) The specific heat capacity of the same material and the thermal conductivity in the same direction are equal and are not affected by the changes in the temperature and SOC.

To simulate the temperature field of the battery pack, the heat generation rate inside the battery cell first needs to be determined, but it is very difficult to accurately obtain it, so it is usually described by a mathematical model. Currently, the Bernardi heat generation rate model proposed by Bernardi et al. [10] from the University of California, Berkeley, USA, is commonly used. In this model, the heat generation rate of the battery cell is assumed to be uniformly distributed inside the battery cell. The following is the equation used to determine the heat generation rate q:

$$q=\frac{I}{V_b}\left[\left(E_0-U\right)-T\frac{dE_0}{dT}\right] \tag{1}$$

Where I is current ($I < 0$ for discharge), V_b is the cell volume, E_0 is open circuit voltage, U is the cell terminal voltage, T is temperature and dE_0/dT is the temperature influence coefficient, generally 0.4 mV/K [11]. $IT(dE_0/dT)$ and $I(E_0 - U)$ are the reversible heat and irreversible heat generated during the discharge of LIB, respectively. Since $E_0 - U = IR_{cell}$, R_{cell} is the total internal resistance of the battery cell, the formula (1) can be changed to:

$$q=\frac{1}{V_b}\left[I^2R_{cell}-IT\frac{dE_0}{dT}\right] \tag{2}$$

When the battery pack reaches the temperature equilibrium state, the Newton's law of cooling is as follows:

$$\phi=h\left(T-T_0\right) \tag{3}$$

Where ϕ is the heat flux, h is surface convection heat transfer coefficient, T is the surface temperature of the battery and T_0 is the temperature of the cooling medium.

2.3 Mesh model

In this study, ANSYS SCDM was used to build the three-dimensional geometric model of the battery pack, ICEM was used for the meshing, and ANSYS FLUENT was used for the simulation and analysis. In FLUENT, a three-dimensional dual-precision transient solver model with a time step of 1 s is employed. The battery pack surface maximum temperature T_{max} and the maximum temperature difference ΔT_{max} are taken as monitoring targets and are also used to evaluate the cooling effect of the battery pack thermal management system.

$$\Delta T_{max}=T_{max}-T_{min} \tag{4}$$

Here, T_{max} and T_{min} are the battery pack surface maximum temperature and minimum temperature, respectively.

3. RESULTS AND DISCUSSION

3.1 Model verification

This study uses a Ningbo Bate (NBT) battery testing system to control the charging and discharging processes of the battery cell. And an infrared imager is used to measure the surface temperature distribution of the battery cell. To verify the reliability of the numerical analysis, the experimentally measured surface temperature of the battery cell at different discharge rates is compared with the simulation results. Figure 2 shows the comparison of the simulated and experimental results of the battery surface maximum temperature during 1C, 2C, and 3C discharges under the conditions of ambient temperature (25 ℃) and natural convection.

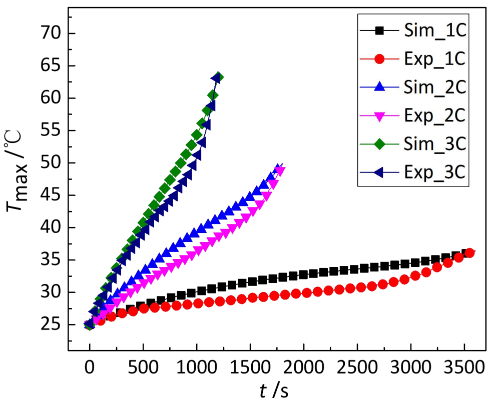


Fig 2 Comparison of simulation with experiment

Comparing the experimental and simulated maximum temperature variation curves (Figure 2), it can be found that although the discharge rates are different, the simulated values are in good agreement with the experimental values at the beginning and end stages of the discharge; however, the simulated values are slightly higher than the experimental values at the middle stage of the discharge; this is more obvious under 1C discharge. This is because when calculating the heat generation rate of the cell, the influence of reversible heat with the change in the depth of discharge (DOD) was neglected (i.e., the reversible heat was considered a constant value), and the reversible heat accounts for a larger proportion of the total heat generation at low discharge rates. Therefore, the difference is greater under 1C discharge, and the maximum error is 2.9 ℃, based on which the simulation result can be considered reliable.

Based on the verified battery cell thermal model, the temperature field of the battery pack under two thermal management methods is simulated and analyzed, as listed in Table 2. Figure 1 shows the structure of the models.

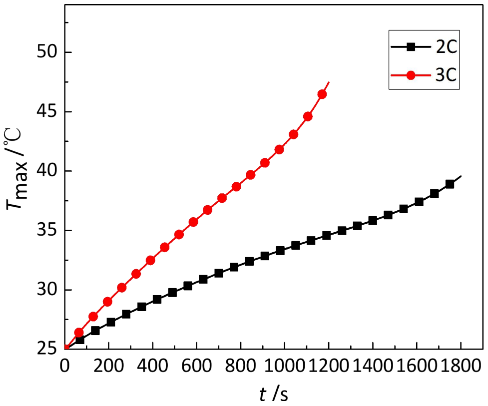
Table 2 Thermal management methods of the battery pack

	Thermal management method
Case 1	Fin forced convection cooling method
Case 2	Composite cooling (fin and PCM) method

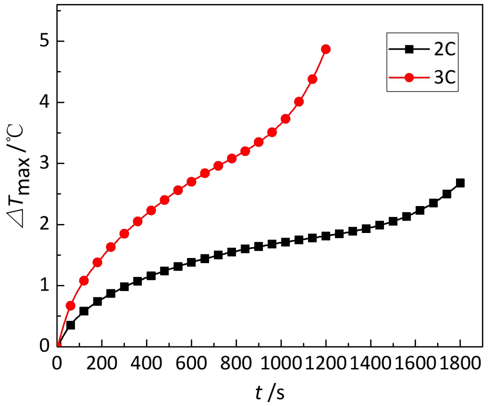
3.2 Temperature field characteristics of battery packs

3.2.1 Fin forced convection cooling

To analyze the thermal characteristics of the battery pack at high discharge rates, first, the temperature field of the battery pack under fin forced convection condition was simulated. Figure 1(a) shows the structure of the model. Figure 3 shows the variation in the surface maximum temperature and the maximum temperature difference of the battery pack with time under 2C and 3C discharges for an air flow rate of 2 m/s.



(a) Maximum temperature



(b) Maximum temperature difference

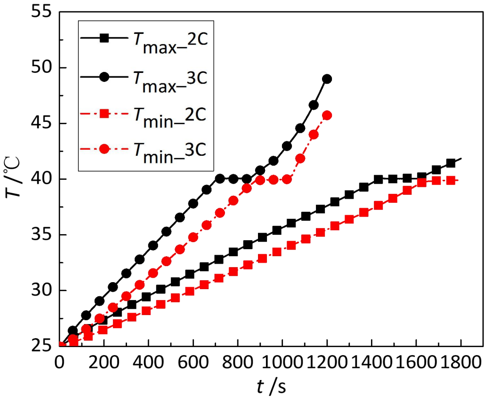
Fig 3 Thermal characteristics of the battery pack (Case 1)

The figure shows that the maximum temperatures of the battery pack at the end of 2C and 3C discharges are 39.6 and 47.5 ℃, respectively, and the maximum temperature differences are 2.7 and 4.9 ℃, respectively. Installing the fins helped achieve a better cooling effect, not only significantly reducing the maximum temperature of the battery pack, but also maintaining the maximum temperature difference in the optimum range. This is mainly because the copper plate with a high thermal conductivity quickly transferred the heat generated by the battery pack to the fin part, and the heat was then taken away by forced ventilation, thus slowing down the temperature rise of the battery pack.

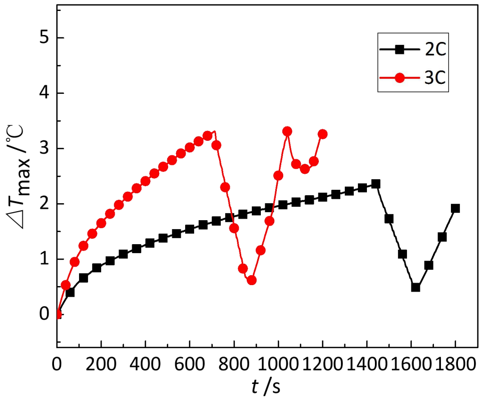
3.2.2 Composite cooling (fin and PCM)

Considering the complexity of the fin ventilation device, a composite cooling method combining the PCM and the fin is considered to control the temperature rise and non-uniformity of the battery pack by taking advantage of the endothermic property of the PCM and the high thermal conductivity of the fin. In this study, the PCM is placed between the battery and the copper fin and filled on both sides of the fin, as shown in Figure 1(b).

Figure 4 shows the temperature variation curves of the battery pack. Under 3C discharge, although the maximum temperature is slightly higher than 45 ℃, the maximum temperature difference is only 3.3 ℃. The composite cooling method (fin and PCM) effectively improved the uniformity of the temperature between the batteries.



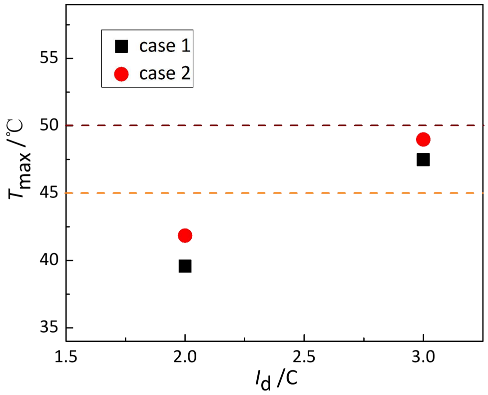
(a) Maximum and minimum temperature



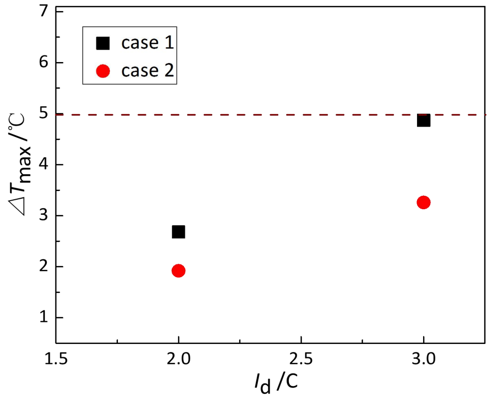
(b) Maximum temperature difference

Fig 4 Thermal characteristics of the battery pack (Case 2)

The temperature curves of 2C and 3C discharge processes show that the surface maximum temperature remains constant after rising to a certain value and then increases rapidly. At the same time, the maximum temperature difference increases first, then decreases and then increases again, and at the end of 3C discharge shows a slight decrease again. This is mainly because during the discharge process, the PCM first absorbs the heat generated by the battery in the form of sensible heat and then begins to phase change and absorbs a large amount of heat in the form of latent heat when reaching the melting point temperature. At this point, the maximum temperature remains largely unchanged, while the minimum temperature continues to increase, thus rapidly decreasing the temperature difference. Thereafter, the PCM near the maximum temperature region completely melts, whereas the PCM near the minimum temperature region does not, thus rapidly increasing the maximum temperature difference with the increase in the maximum temperature. After the PCM near the minimum temperature region completely melts, the minimum temperature increases sharply, thus slightly decreasing the maximum temperature difference again.



(a) Maximum temperature



(b) Maximum temperature difference

Fig 5 Comparison of thermal management effect under different cooling methods (Air flow rate: 2 m/s)

Finally, the thermal management effect of the battery pack under the two cooling methods at the end of 2C and 3C discharges was comprehensively compared. Figure 5 shows the results.

Figure 5 shows that at high discharge rates (2C and 3C), the fin forced convection cooling and composite cooling (fin and PCM) methods effectively reduce the maximum temperature and maximum temperature difference of the battery pack. Although the maximum temperature is slightly higher than 45 ℃, the maximum temperature difference is less than 5 ℃, and when using the composite cooling method, the uniformity between the batteries is better.

4. CONCLUSION

In this study, a CFD method was used to simulate and study the thermal management effect of a battery pack when using fin forced convection cooling and composite cooling (fin and PCM) methods under different operating conditions. The following are the conclusions drawn from this study:

(1) The fin forced convection cooling method could reduce the maximum temperature of the battery pack and control the maximum temperature difference of the battery pack within the optimum operating temperature range.

(2) When using the composite cooling (fin and PCM) method, the maximum temperature of the battery pack was basically the same as that when using fin forced convection cooling at low air flow rates; however, the maximum temperature difference of the battery pack obviously decreased. Thus, the overall cooling effect was better than that provided by fin forced convection cooling. Moreover, the system of the composite cooling method is simpler, making it a preferable thermal management method.

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