The Analysis of Battery Cooling Modes of EV

Yue Yang, Pengyu Wang, Guangming Lu, Hang Dong, Feng Li and Yanru Suo

Abstract In this paper, the lithium battery for electric vehicles is used. The working principle and the heating principle of the battery are analyzed. Based on the battery heating principle, the performance of the existing battery cooling mode is qualitatively analyzed. Battery heating model is established on the basis of which different battery cooling models are established, including air cooling mode, indirect water cooling mode, and direct liquid cooling mode. Compared with the air cooling mode, the cooling effect of the liquid cooling mode is more obvious, and the range of temperature of the battery cell in battery packs is much smaller in the liquid cooling mode.

Keywords Battery · Cooling system · Cooling modes · Simulation

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1 Introduction

The development of electric vehicles (EVs) has received wide attention from the society and strong support from the government and has become an important product in the field of new energy vehicles. The electric vehicle is powered by the battery pack, and the performance of the battery pack directly affects the performance of the electric vehicle. The performance of the battery pack is strongly influenced by temperature. The battery capacity, life, and efficiency will decline and even cause an accident, if the temperature is too high. Therefore, it is necessary to control the temperature of the battery in a reasonable temperature range. In this paper, a battery pack model is built based on AMESim, and different forms of cooling system in the model are simulated, in order to contrast the control effect of different cooling forms of the battery temperature.

2 Battery Heating Principle

2.1 Working Principle of Lithium Battery

The working process of lithium ion battery is actually that lithium ion intercalates and deintercalates in negative and positive electrodes through electrolyte and diaphragm [1–4]. The working principle is shown in Fig. 1.

While the battery is charged, the electrons run from the positive electrode to the negative through the external circuit. At the same time, lithium ions deintercalate from the positive electrode and move to the negative through the diaphragm, combining with the electron and intercalating into carbon materials. The more the lithium ion is intercalated, the higher the charging capacity is. In contrast, when discharging, the electrons run from the negative electrode to the positive electrode through the external circuit. Simultaneously, lithium ions deintercalate from the

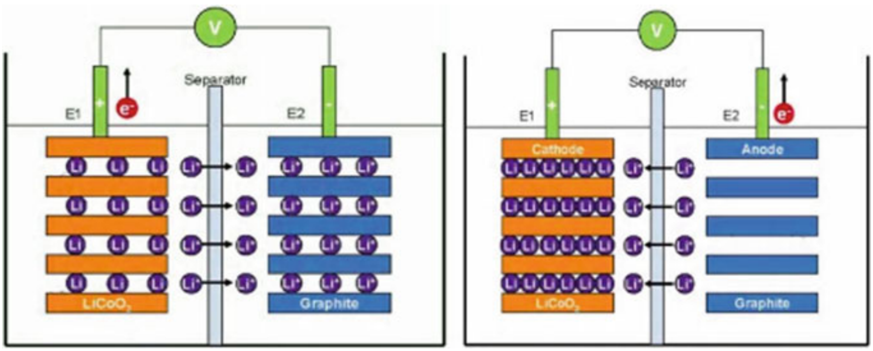


Fig. 1 Working principle of lithium ion battery

negative electrode and move back to the positive electrode. The more the lithium ions move back to the positive electrode, the higher the discharging capacity is. As the process of charging and discharging is going on, lithium ions intercalate in and deintercalate from the positive and negative electrodes repeatedly.

2.2 Lithium Ion Battery Heating Model

In 2001, Sato et al. in Honda Automotive Co., Ltd [5] verified a model for calculating the thermal power of a battery by experiments, and applied it in Ni-MH batteries and Li-ion batteries. They thought that the internal heat of the battery is divided into four parts, that is, the electrochemical reaction heat, the side reaction heat, the ohmic heat, and the polarization heat. Among them, the electrochemical reaction heat is generated from the internal chemical reactions when batteries are working, and it is a negative value when charging and a positive one when discharging. The polarization heat, a positive value, is the energy loss caused by electrode potential deviating from equilibrium electromotive force. The Joule heat is the heat that is generated by the internal resistance of the battery, which is always positive. The side reaction heat, which is generally very small and almost negligible for lithium batteries, is mainly generated by the self-discharge, electrolyte decomposition, and other factors. The calculation model of electrochemical reaction heat Q_r is shown in formulas (1)–(4).

$$Q_r = -T\left(\frac{\delta(\Delta G)}{\delta T}\right) \tag{1}$$

$$\Delta G = -nFE \tag{2}$$

$$Q_r = nFT\left(\frac{\delta E}{\delta T}\right) \tag{3}$$

$$Q_r = \frac{Q_1}{F/3600} I_\mathrm{c} = -0.0337 Q_1 I_\mathrm{c} \tag{4}$$

In the formula, n is the amount of substance of the electrons participated in the reaction, and the unit is mol. I_C is the charging current, and the unit is A. E is equilibrium electromotive force, and the unit is V. F is the Faraday's constant, and the value is 96,484.5 C/mol. Q_1 is the total heat generated by the charging of the positive and negative electrodes, and the unit is KJ/h.

The calculation models of the polarization heat Q_p and the ohmic heat are shown in formulae (5)–(6).

$$Q_p = I^2R_p(W) = 3.6I^2R_p(\text{KJ/h}) \tag{5}$$

$$Q_e = I^2R_e(W) = 3.6I^2R_e(\text{KJ/h}) \tag{6}$$

R_p and R_e are, respectively, polarization resistance and ohmic resistance, and the unit is Ω.

3 The Analysis of Battery Cooling Mode

Battery thermal management type is classified according to the heat-transfer medium [6–9], and is generally divided into air cooling, liquid cooling, and phase-change material cooling.

3.1 Air Cooling System

Without using any external auxiliary power, the air cooling system directly uses the natural wind to take away the heat of the battery. The system is simple, and the cost is low. At present, there are two kinds of air cooling ventilation modes, serial and parallel. As for serial ventilation mode, as shown in Fig. 2, cold air blows in from the left and blows out from the right. The air is gradually heated by the battery, so the air temperature gets higher and higher and the cooling effect becomes worse and worse from the left to the right. The battery temperature increases from left to right in the battery box, resulting in the inconsistency of the distribution of the battery module temperature, which affects the cooling effect of the battery.

Parallel ventilation makes the airflow more evenly distributed among the battery modules, which ensures the consistent distribution of battery pack temperature field. The parallel ventilation mode is shown in Fig. 3.

It can be seen that the main advantages of the air cooling mode are as follows:

(1) The structure is simple, and the weight is relatively small; (2) there is no possibility of liquid leakage; (3) there is effective ventilation when harmful gas is produced; and (4) it is of low cost.

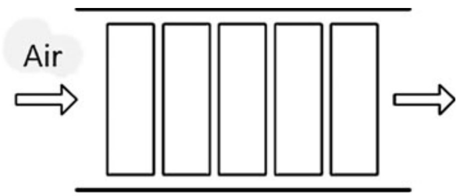


Fig. 2 Serial air cooling

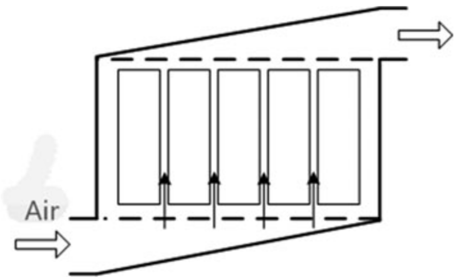


Fig. 3 Parallel air cooling

The disadvantage is as follows: The heat-transfer coefficient between the air and the cell surface is low, so the cooling and heating rates are slow.

3.2 Liquid Cooling System

Compared with air, liquid has a relatively high heat-transfer coefficient. Therefore, the heat generated by batteries can be quickly taken away and the battery temperature can be effectively reduced.

Liquid cooling is mainly divided into direct-contact mode and indirect-contact mode.

Indirect-contact liquid cooling system must integrate the sleeve and other heat-transfer facilities with the battery pack in order to achieve the cooling effect, which, in some way, reduces the efficiency of heat transfer and increases the complexity of the design and maintenance of the thermal management system.

Direct-contact liquid cooling systems usually use non-conduction heat-transfer materials with high heat-transfer coefficient, such as mineral oil and ethylene glycol. As for indirect-contact liquid cooling system, water and antifreeze fluid are usually used as heat-transfer material.

Performance comparison of different cooling modes is shown in Table 1.

Table 1 Performance comparison of different cooling modes

Item	Cooling modes		
	Air cooling	Indirect water cooling	Direct liquid cooling
Ease of use	Easy	Medium	Medium
Ease of integration	Easy	Difficult	Difficult
Cooling ability	General	Medium	High
Refrigeration consistency	Low	Medium	High
Easy maintenance	Easy	Medium	Difficult
Initial cost of system	Low	High	High

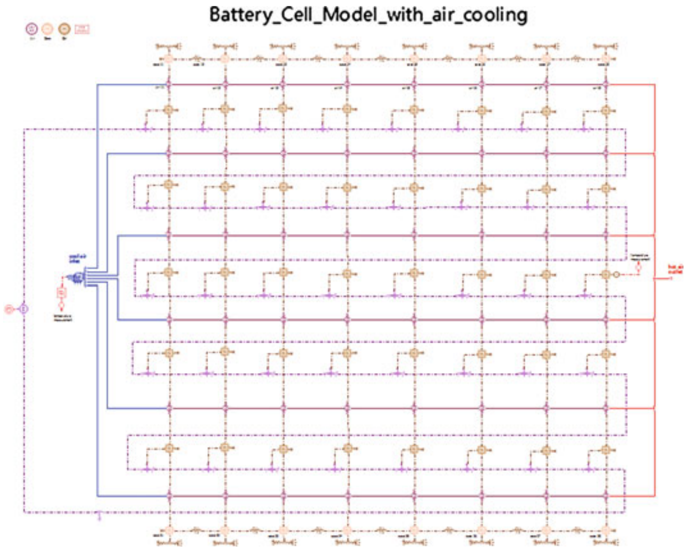


Fig. 4 Air cooling battery pack model

4 Build the AMESim Model of Power Battery Pack and Its Cooling System

According to the analysis above, the battery pack model is built using AMESim in this paper. The ambient temperature is 30 °C. In the battery pack, there are 40 series of battery monomers. The battery pack takes the power consumed by an EV in 4 consecutive EPA-US06 cycles as its current source. The model builds the heat capacity of a single cell and that of the battery shell. In this paper, the heat capacity of one side of the battery shell is divided averagely into 8 parts to replace the single heat capacity. The model also builds the heat-exchange interface between each cell of the battery, the heat-exchange interface between the battery and the battery shell, and the heat-exchange interface between the battery shells. The model is shown in Figs. 4 and 5. Figure 4 shows the air cooling battery pack model. The liquid cooling battery pack model is shown in Fig. 5. Both direct and non-direct liquid cooling systems can be achieved in the same liquid cooling battery pack model.

5 Simulation Result Analysis

Conducting the simulation analysis in AMESim, the average temperature rise curves of the 40 battery cells in the battery pack in three cooling modes are obtained, as shown in Fig. 6. It can be seen that the temperature raises 25.14 °C

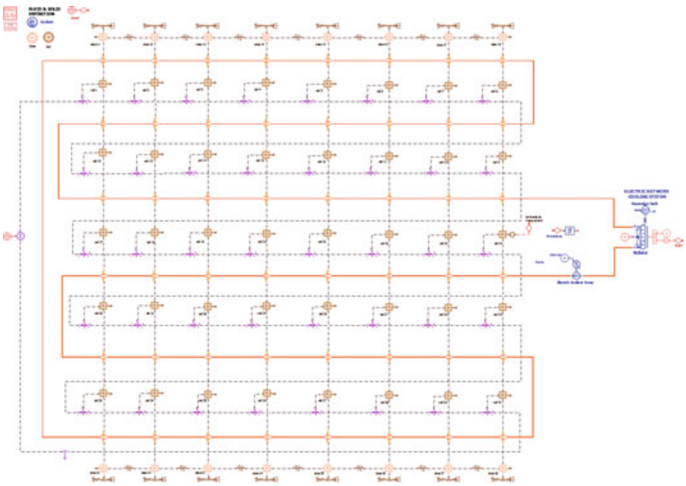


Fig. 5 Liquid cooling battery pack model

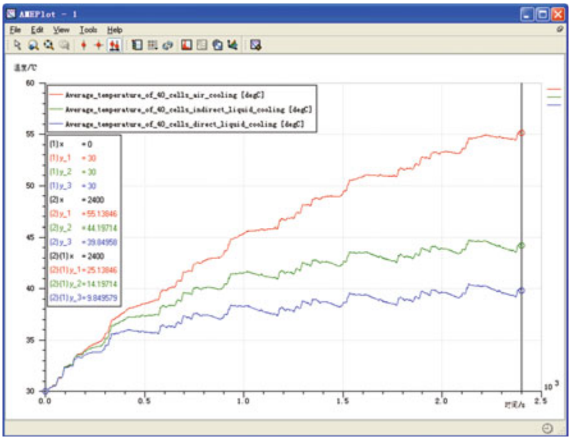


Fig. 6 Average temperature rise curves of the 40 battery monomers in the battery pack

under the air cooling mode, 14.2 °C under non-direct liquid cooling mode, and 9.85 °C under direct liquid cooling mode. When the initial ambient temperature is 30 °C, the battery temperature rises to 55.14 °C under air cooling mode, 44.2 °C under non-direct liquid cooling mode, and 39.85 °C under direct liquid cooling mode. Figure 7 shows the average heat-exchange ratio under 3 modes. It is shown in Fig. 7 that the battery heat-exchange ratio under direct liquid cooling mode is significantly higher than that under air cooling mode.

Take the final temperature of the 40 battery monomers under 3 cooling modes as one set of data. The mean square deviation is shown in formula.

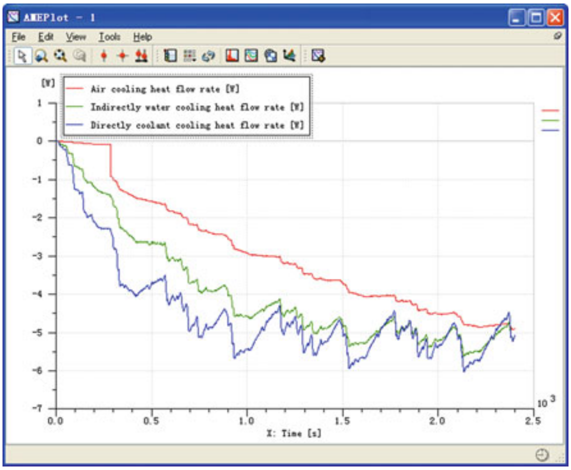


Fig. 7 Battery monomer average heat-exchange ratio curves

Table 2 Comparison of simulation results of different cooling modes

Contrasting parameter	Cooling modes		
	Air cooling	Indirect water cooling	Direct liquid cooling
Final temperature at the end of simulation (°C)	55.14	44.2	39.85
Elevated temperature (°C)	25.14	14.2	9.85
Mean square deviation of the final temperature of all monomers	0.9392	0.0289	0.0162

$$\sigma = \sqrt{\frac{1}{N}\sum_{\text{i=1}}^{N}(x_i - \mu)^2} \tag{7}$$

$$\mu \frac{\sum_{i=1}^{N} x_i}{N} \tag{8}$$

The comparison of simulation results of different cooling modes is shown in Table 2.

6 Analysis of the Characteristic of Battery Temperature

In this paper, the charging or discharging process of a lithium ion battery with a nominal capacity of 180 A h is tested, and the battery charging or discharging efficiency is calculated. Charging or discharging efficiency is defined as follows:

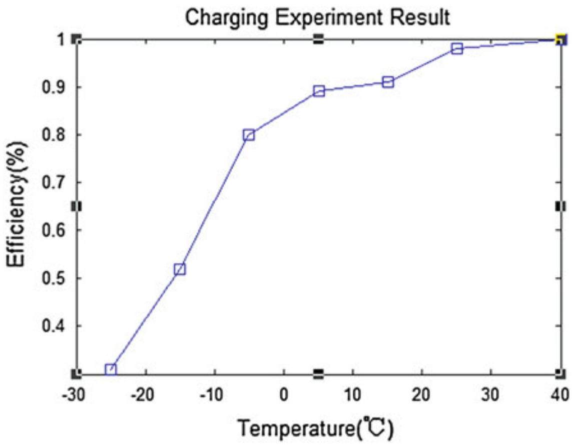


Fig. 8 Charging efficiency curve

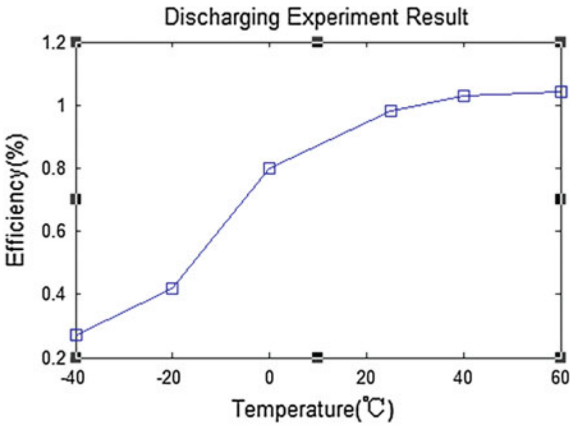


Fig. 9 Discharging efficiency curve

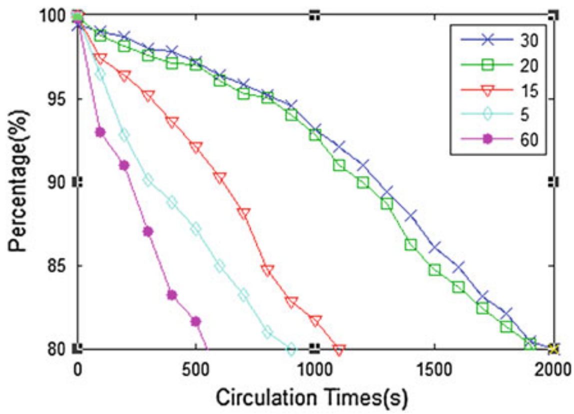
$$\text{Charging/discharging efficiency} = \frac{\text{Actual Charging/Discharging Capacity}}{\text{Nominal Capacity}}$$

Charging efficiency curve is shown in Fig. 8. Discharging efficiency curve is shown in Fig. 9.

When the circulating capacity reduces to 80 % of the nominal capacity, take that 80 % nominal capacity as the end of the battery's life. The cycling life curve of the battery at different temperatures is shown in Fig. 10.

For charging, when the temperature is above 5 °C, a high efficiency can be guaranteed and can reach more than 90 %, as shown in Figs. 8 and 9. For discharging, the temperatures need to reach 20 °C to guarantee more than 90 % efficiency, as shown in Figs. 8 and 9. When the temperature is between 30 and 40 °C, both charging and discharging efficiency can reach 95 % or more. The battery life is the maximum when the temperature is 30 °C and is obviously decreased at a

Fig. 10 Relationship of battery life with temperature



relatively high temperature 60 °C and a relatively low temperature 15 °C, as shown in Fig. 10. So it can be obtained that when the temperature is between 30 and 40 °C, the battery life reaches to its maximum.

It is seen from the simulation results of the model that when the initial temperature is 30 °C, both direct liquid cooling and indirect water cooling modes are able to control the battery temperature within 40 °C, but the effect of air cooling is not ideal. Therefore, liquid cooling can satisfy the requirements, and in the actual use, we can choose indirect water cooling or direct liquid cooling according to the situation.

7 Conclusion

The operating temperature of a battery is an important parameter for charging and discharging, and the working efficiency and service life of the battery will be limited if the temperature is too high. The heating principle of lithium ion battery, followed by an analysis of three battery cooling modes, is first analyzed in this paper, and the characteristics of them are compared. A lithium ion battery pack model was built in the AMESim software, and the model of the three cooling modes was established, respectively. Under the same environment temperature and working cycle, the cooling capacity of the three cooling modes and the temperature difference between each two battery monomers in the battery pack were compared and analyzed. Based on the experiment, the conclusion is drawn that the charging or discharging efficiency and the service life of the battery will be kept at a higher level when the battery temperature is between 30 and 40 °C. The simulation results show that compared with the air cooling mode, under water cooling mode, the battery can get enough cooling, so that the battery can work within an appropriate operating temperature range and the battery temperature differences between each two monomers are relatively small. The cooling effects of indirect water cooling and direct cooling are not much different, and the difference between each two battery monomers is also small. Therefore, indirect water cooling is a suitable battery cooling mode.

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