Research on Cooling Characteristics of Power Battery Fast-charging of Refrigerant-based Direct Cooling System

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Abstract. In this paper, the temperature variation characteristics and control methods of power battery during rapid charging are studied. For the problem of large heat production in power battery fast-charging process, a refrigerant-based direct cooling battery thermal management system were built based on the AMEsim one-dimensional simulation platform. The change law of the battery temperature and the influence of different types of control thresholds on the cooling effect and the thermal management boundary of the cooling process in the constant current charging method of were studied. The results show that in the cooling process with the temperature as the threshold value, the cooling response is good under the condition of lower C-rate. With the increase of the C-rate, the temperature threshold cooling can not meet the cooling response requirements. Based on the consequence, the battery’s SOC(state of charge) was proposed as the control threshold signal for the advance cooling. The simulation results show that the SOC threshold cooling can control the highest temperature of the battery below 40°C, meeting the requirements of battery operation request. Through the full cooling of the maximum power, it is obtained that the thermal management boundary C-rate decreases linearly with the initial temperature change, and the final temperature in different initial temperatures increases linearly with the increase of the C-rate.

Keywords: Fast-charging; Battery thermal management; Refrigerant-based direct cooling system; AMEsim; the response of cooling; Threshold control.

1. Introduction
Environmental protection has become an issue that people pay more and more attention to in social life, and the emissions of traditional fuel vehicles are a relatively large part of environmental pollution. The emergence of pure electric vehicles has alleviated this important pollution problem. Its zero-emission and high-efficiency energy conversion characteristics are well received by consumers. As the core of pure electric vehicles, power battery performance and safety are particularly important. An important parameter that affects the performance and safety of power batteries is the temperature. Power batteries have high requirements for temperature, so thermal management technology is needed to highlight its important position.

With the emergence of fast charging technology, the battery is charged at a high C-rate to shorten the charging time of the battery. Common charging methods include constant current charging method, constant voltage charging method, constant current and constant voltage charging method, variable current charging method, and pulse charging method[1]. In the fast charging process, the characteristics of high C-rate and high current lead to high heating power of the battery, and the disadvantages of uneven temperature distribution will have a great impact on the performance and safety of the battery.
Therefore, thermal management technology during fast charging is extremely important. The direct cooling method combines the battery cooling system with the automobile air conditioning system. The battery cooling plate is directly used as the evaporator of the air conditioning system, and the refrigerant is directly used as the refrigerant of the heat management system. The phase change latent heat is used for cooling, which has a high heat exchange capacity, suitable for cooling high heat production processes. Jiao Lichun, Sun Weiyi, Ding Yi and others have carried out optimization research on the fast charging strategy of power battery\(^\text{[2]}\)\(^\text{[3]}\)\(^\text{[4]}\), Jeong, Mun Goung and others have conducted heat transfer analysis on high-power power battery and established the basis thermal model of unit composition and comparison of different unit numbers of model\(^\text{[5]}\). Jiuyu Du et al. studied the boundary of high-power charging of batteries from the perspective of heat production, and the results show that for the power battery can be charged to 80% of the power at the charge C-rate of 4 C and below, which is the boundary of high-power charging. Depends on the performance of thermal management\(^\text{[6]}\). Dong, Ti et al. studied the thermal behavior of the NCM lithium battery during the charging and discharging process by numerical simulation. By comparing the charging and discharging process, they found that the discharge process of the same rate is more likely to cause thermal runaway\(^\text{[7]}\). Chen Siqi et al. designed a heat management system based on liquid cooling, and proposed a neural network model to predict the optimal fast charging cooling scheme to control the energy consumption of the charging process cooling\(^\text{[8]}\). Jaguemont, Joris and others studied the thermal effect of the battery's charging process by means of three-dimensional simulation, and this model can well show the battery's change process from two perspectives of electric and thermal\(^\text{[9]}\). Bao Yun et al. used a combination of experiment and simulation to study the air cooling fast charging process. By comparing the external air circulation and the internal air circulation, the results showed that the external circulation can save 69.4% of the energy consumption than the internal circulation\(^\text{[10]}\). Zheng Yiran et al. optimized the liquid cooling to the fast charging process, combining liquid cooling and phase change cooling, the overall cooling system can well control the battery temperature during the fast charging process\(^\text{[11]}\). Yuanmeng built an experimental platform for the basic functions of the refrigerant-based direct cooling heat management system to study its system and the thermal characteristics of the power battery\(^\text{[12]}\). Deng Fan used a refrigerant-based direct cooling power battery thermal management system to conduct experiments to study the cooling characteristics of the heat load change system and analyze the resistance characteristics of the cooling pipe\(^\text{[13]}\).  

In this paper, a refrigerant-based direct cooling battery thermal management system model is established based on a one-dimensional simulation platform AMEsim, and the cooling process, responsiveness and thermal management boundary of the power battery fast charging process are studied. Through the cooling of the charging process, the law of temperature change is analyzed, and the influence of temperature and SOC as the cooling threshold on the battery temperature is compared. Use the maximum power of the thermal management system to cool the entire process to explore the thermal management boundary of fast charging. Provide a data basis for the formulation of dynamic control strategies for the fast charging process of power batteries. The abbreviations mentioned in the article are shown in Table 1.

| Abbreviations | Description |
|---------------|-------------|
| SOC           | State of charge |
| DOD           | Depth of discharge |
| NCM           | Ni-Co-Mn |
| OFF           | Official data |
| SIM           | Simulation result |
| EXP           | Experimental result |
| ERROR         | The error between official data or experimental result with simulation result |
| \(V_{\text{oc}}\) | The open circuit voltage |
| HT            | Highest temperature |
| FT            | Final temperature |
| C-rate        | The ratio of the operating current to the rated capacity current of the battery |
2. Power Battery and Refrigerant-based Direct Cooling System Model Establishment and Verification

2.1. Establishment and Verification of Battery Thermoelectric Model

2.1.1. Establishment and verification of battery thermal model.

In the process of discharging and charging the power battery, the conversion of electrical energy and chemical energy occurs. However, in addition to the mutual conversion of these two energies, it also continuously generates heat. During battery operation, the temperature of the battery will continue to increase due to the generation and accumulation of heat. The heat generation rate \( q \) of the battery is calculated by Bernadi heat generation equation [14]. Assuming that the heat generation rate inside the battery is uniform, the heat generation rate \( q \) during the charging and discharging process of the battery:

\[
q = I(U - U_0) + IT \frac{\partial U}{\partial T} = I^2R + IT \frac{\partial U}{\partial T}
\]  

(1)

Where \( I \) is the current when the battery is charged or discharged, \( U_0 \) is the open circuit voltage of the battery, \( U \) is the operating voltage of the battery, and \( R \) is the internal resistance of the battery, including ohmic internal resistance and polarization internal resistance, also known as overpotential resistance, \( \frac{\partial U}{\partial T} \) is the partial derivative of the battery's open circuit voltage to the battery temperature, called the entropy heat coefficient.

In (1), for the two terms on the right side of the equation, the first term is the heat generated due to the existence of internal resistance, this part of heat is irreversible, called irreversible resistance heating, and the second term is the reversible entropy heat of the electrochemical reaction of the battery Heat, and the entropy heat coefficient \( \frac{\partial U}{\partial T} \) is considered to be a fixed constant under a fixed SOC, so it changes with the change of SOC.

According to the first law of thermodynamics, without considering the convective heat transfer inside the battery and the radiation heat transfer outside the battery, the energy conservation equation is:

\[
\rho \frac{\partial T}{\partial t} - \lambda_\alpha \frac{\partial^2T}{\partial x^2} + \lambda_\beta \frac{\partial^2T}{\partial y^2} + \lambda_\gamma \frac{\partial^2T}{\partial z^2} + q - q_h
\]  

(2)

In the equation: \( \rho \) is the density of the battery, and the average density is simplified as the ratio of mass to volume of the battery. \( c \) is the specific heat capacity, which is obtained by the average weighting method of the mass of different materials of the battery. \( \lambda_{\alpha,\beta,\gamma} \) is the different thermal conductivity of the battery in three directions, \( q \) is the heat production rate of the battery, and \( q_h \) is the heat dissipation rate of the battery.

For the battery heat generation model, the official temperature change with SOC(state of charge) and DOD(depth of discharge) data of Samsung SDI 94 Ah battery is selected as the comparison standard, as shown in the Figure 1. The specifications of the Samsung SDI 94 Ah battery used in the model are shown in Table 2.

| Parameter                  | Unit   | Value  |
|----------------------------|--------|--------|
| Capacity                   | Ah     | 94     |
| Nominal voltage            | V      | 3.7    |
| Operating voltage          | V      | 2.8-4.2|
| Size                       | Mm     | 173*125*45 |
| Cell weight                | kg     | 2      |
| Density                    | Kg/mm³ | 2055   |
| Specific heat capacity     | J·kg⁻¹·K⁻¹ | 900   |
| Thermal conductivity       | W·kg⁻¹·K⁻¹ | 18        |
| Battery pack structure     | —      | 96S    |
2.1.2. Establishment and verification of battery electric model.

The electrical model of the battery adopts the second-order Thevenin model [15] in the equivalent circuit model, which considers the ideal voltage source, resistance and capacitance to characterize its electrical characteristics. Thevenin model is shown in the Figure 2.

Where OFF is expressed official data and SIM is expressed simulation data. The simulation process simulates the charging and discharging process of the battery with different C-rate at 25°C to verify the temperature change. In the process of battery charging or discharging, due to the thermal effect of current and the existence of electrochemical reaction, the temperature of the battery will continue to rise, and the higher the charging or discharging multiplier, the higher the temperature rise of the battery will be. Therefore, when verifying the thermal model of the battery, the temperature rise of the battery in these two processes is selected as the verification quantity. Due to the existence of differential equation in the process of model establishment, the difference of iteration times and the systematic error of official test data. The result shows that the relative error value is within 5%, which is within the acceptable range [16].

Figure 1. Battery temperature.

Figure 2. Second order Thevenin equivalent circuit model.

In the figure 5, $U_{oc} (SOC)$ is the open circuit voltage of the battery. At a certain temperature, it is a function of the battery SOC; $R_0$ is the ohmic internal resistance of the battery; $U_I$ is the operating voltage of the battery, and $C_i$ and $R_i$ are the battery’s Electrochemical polarization capacitance and internal
resistance; $C_i$ and $R_i$ are characterized by the concentration difference polarization and internal resistance of the battery. $I$ is the operating current. The calculation relationship is

$$U_i = U_{soc}(SOC) - U_i - R_i I$$

(3)

$$\frac{dU_i}{dt} = -\left(\frac{U_i}{R_i C_i} + \frac{I}{C_i}\right)$$

(4)

$$\frac{dU_i}{dt} = -\left(\frac{U_i}{R_i C_i} + \frac{I}{C_i}\right)$$

(5)

$$\frac{d(SOC)}{dt} = \frac{I}{3600C_{th}}$$

(6)

In the equation: internal resistance $R_{s,l}$ and capacitance $C_{s,l}$ are all functions of SOC and temperature $T$, which are generally measured through experiments. $C_{th}$ is the capacity of the battery. Combining with the electric and thermal model of the battery, first calculate the average temperature of the battery, and input this parameter into the equivalent circuit model for calculation. The simulation process simulates the $V_{oc}$(open circuit voltage) of the battery 1C-rate and 2C-rate during charging and discharging, and the results are shown in the Figure 3.

![Figure 3. Battery open circuit voltage.](image)

In the battery charging process, the open-circuit voltage of the battery increases with the increase of the battery SOC, and the increase amplitude increases with the increase of the charging C-rate. Similarly, in the discharge process, the open-circuit voltage decreases with the increase of the SOC of the battery, and the decline amplitude increases with the increase of discharge C-rate. The error between the simulation value and the true value of the open circuit voltage does not exceed 5%, which is within the acceptable range.

2.2. Establishment and Verification of Refrigerant-based Direct Cooling System

2.2.1. Establishment of refrigerant-based direct cooling system.

The refrigerant-based direct cooling system is to transform the air-conditioning system and replace the evaporator with an evaporative cooling plate. The refrigerant evaporates in the plate and directly exchanges heat with the battery. The system diagram is shown in the Figure 4.
When establishing the compressor model, because this paper studies the systematic cooling process control, combined with the simulation platform, the simplified compressor model is selected, and the volumetric efficiency, isentropic efficiency, and mechanical efficiency are considered to control the compressor model. The calculation process is as follows\(^{(1)}\) (Simcenter Amesim User’s guide library Air-Conditioning Compressor):

\[
m_f = \eta_v \cdot \rho_{suc} \cdot N \cdot \text{disp}
\]  

Where \(m_f\) is the mass flow, \(\eta_v\) is the volumetric efficiency, \(\rho_{suc}\) is the suction density, \(N\) is the speed of the compressor, and \(\text{disp}\) represents the displacement of the compressor.

\[
\eta_{is} = \frac{h_{dis} - h_s}{h_d - h_s}
\]  

Where \(\eta_{is}\) is the isentropic efficiency, \(h_{dis}\) is the isentropic exhaust specific enthalpy, \(h_s\) is the suction specific enthalpy, and \(h_d\) is the exhaust specific enthalpy, \(m\) is the mass of fluid.

\[
h_{inc} = h_d - h_s = \frac{h_{dis} - h_s}{\eta_{is}}
\]  

\[
dm \cdot h_{out} = -dm \cdot h_{in} + dm \cdot h_{inc}
\]  

Where \(h_{out}\) is the compressor discharge enthalpy, \(h_{in}\) is the compressor suction enthalpy.

\[
\eta_{mech} = \frac{dm \cdot h_{inc}}{\tau \cdot N}
\]  

Where \(\eta_{mech}\) is the compressor mechanical efficiency, \(\tau\) is the torque, and \(N\) is the compressor speed.

The modeling of the condenser and the refrigerant-based direct cooling plate is simplified to only consider the heat transfer coefficient of the internal flow, the size parameters of the wall and fins, the external flow heat transfer coefficient and the external thermal conductivity. According to the simulation platform, establish a discrete model of the flow and heat transfer pipes inside the condenser. Schematic diagram of discrete model of heat exchanger is as shown in the Figure 5.

**Figure 4.** Refrigerant-based direct cooling system schematic.
1- Convection heat exchange between air and outer wall
2- Convection heat exchange between refrigerant and pipe
3- Refrigerant flow resistance model
4- Refrigerant volume model

Figure 5. Schematic diagram of discrete model of heat exchanger.

Calculation of convective heat transfer between refrigerant discrete unit and heat exchanger pipe:

\[ \phi_{\text{int},i} = h_{ij} \cdot S_i \cdot (T_{\text{ref},i} - T_{\text{wall},i}) \]  \hspace{1cm} (12)

Where \( \phi_{\text{int},i} \) is the convective heat transfer of discrete units in the heat exchanger pipe, \( h_{ij} \) is the convective heat transfer coefficient, \( S_i \) is the contact area in the pipe, \( T_{\text{ref},i} \) is the refrigerant temperature, and \( T_{\text{wall},i} \) is the wall temperature.

For the condenser, the convection heat transfer coefficient in the tube:

\[ h_{TP} = \frac{0.023 \cdot Re^{0.8} \cdot Pr^{0.4} \cdot \lambda}{D} \left( (1-x)^{0.8} + \frac{3.8 \cdot x^{0.65}}{\rho^{0.38}} \right) \]  \hspace{1cm} (13)

Where \( Re \) is the Reynolds number, \( Pr \) is the Prandtl number, \( \lambda \) is the thermal conductivity of the refrigerant, and \( D \) is the inner diameter of the pipe. \( x \) is the thermal steam quality.

For heat exchange between outside and air:

\[ \varphi_{\text{ext}} = h_A \cdot S \cdot (T_A - T_{\text{wall},o}) \]  \hspace{1cm} (14)

Where \( \varphi_{\text{ext}} \) is the heat exchange between the air and the outer wall, \( h_A \) is the air convection heat transfer coefficient, \( S \) is the heat exchange area of the outer wall, \( T_A \) is the air temperature, and \( T_{\text{wall},o} \) is the outer wall temperature.

\[ h_A = \frac{\lambda_A \cdot Nu}{D_A} \]  \hspace{1cm} (15)

Where \( \lambda_A \) is the thermal conductivity of air, and \( D_A \) is the hydraulic diameter of the air on the outer wall side.

For the fin:

\[ \frac{dT_{\text{wall},i}}{dt} = \frac{\phi_{\text{int},i} + \phi_{\text{ext},i}}{m_i \cdot C_{p,i}} \]  \hspace{1cm} (16)

Where \( \phi_{\text{ext},i} \) is the external heat transfer of the discrete model, \( m_i \) is the refrigerant mass flow in the pipe, and \( C_{p,i} \) is the specific heat capacity of the wall.

The mass flow rate of the expansion valve is calculated from the gas density and pressure before the valve.
When the gas dryness before throttling is \( x_1 < 0.3 \):

\[
\dot{m} = C_q \cdot A \cdot \sqrt{2 \cdot \rho \cdot \Delta P} \tag{17}
\]

Where \( C_q \) is the two-phase correction coefficient, \( A \) is the throttle area, \( \rho \) is the refrigerant density before throttling, and \( \Delta P \) is the pressure difference before and after throttling.

\[
C_q = \frac{1}{(1 + a \cdot x)^l l + (b \cdot x D)^l} X^{\frac{d \ln(l)}{D}} \tag{18}
\]

In the equation: \( a, b, c, d \) correction coefficient, \( l \) is the length of the throttle pipe, \( D \) is the pipe diameter.

\[
X = \frac{x}{1 - x} \sqrt{\frac{\rho_l}{\rho_g}} \tag{19}
\]

Where \( \rho_l \) is the density of the refrigerant liquid phase, and \( \rho_g \) is the density of the refrigerant gas phase.

When \( \mu \geq 0.3 \)

\[
\dot{m} = A \cdot \sqrt{\frac{2 \cdot \Delta P \cdot \rho}{\mu}} \tag{20}
\]

where \( \mu \) is the friction factor \(^{[16]}\).

2.2.2. Verification of refrigerant-based direct cooling system.

Using the refrigerant-based direct cooling thermal management experiment platform to verify the established refrigerant-based direct cooling system model, the experimental platform is shown in the Figure 6.

\[\text{Figure 6. Refrigerant-based direct cooling for thermal management experiment platform.}\]

The system consists of four components (a) Battery pack, (b) Compressor, (c) Condenser, (d) Expansion valve, which together constitute a steam compressed refrigeration cycle, and the battery is cooled by a cold plate under the battery pack. In the experiment, different rotating speeds under fixed 1C discharge C-rate were selected to cool the battery for 1800 seconds, and the reliability of the model was verified.
by comparing the temperature drop effect of the battery in fixed time. The cooling of the battery temperature over a fixed period of time is the main factor in determining the cooling capacity of a system. So the temperature drop method is chosen to verify the reliability of the system\cite{12}. Since the subject of this paper is not the performance analysis of each part, the author omits the verification of four parts and takes the cooling performance of the whole system as the verification standard. The comparison between experimental and simulation results is shown in the Figure 7.

![Figure 7. Battery temperature at different rotate speed.](image)

Where EXP is expressed as experimental data. From the data in the Figure 7, by comparing the temperature changes during the cooling process of the power battery by the simulation system and the experimental platform, and the error between the experimental value and the simulated value is within 5%. This error may be due to chance factors in the course of the experiment, but it is within acceptable limits and the system can be used for subsequent simulation calculations.

3. Establishment of AMESim System Model
Based on the AMEsim simulation platform, build a thermal management system as shown in the Figure 8.
Figure 8. Refrigerant-based direct cooling for thermal management model. The system includes refrigeration module, charging module, control module, battery pack and cooling plate. The function of the control module is to collect the parameters of each part and control the temperature of the battery through calculation and output instructions, mainly including the wireless signal collection module, wireless signal sending module and threshold judgment module. The refrigeration module mainly includes compressor, condenser and expansion valve. The battery pack and the cold plate are mainly used as evaporators for the refrigeration system. The charging module mainly outputs current information for charging the battery. The structure of the power battery pack and cooling plate model is shown in the Figure 9.

Figure 9. Battery pack and cooling plate structural model. Cooling plate specifications are shown in Table 2.
Table 2. Cooling plate specification.

| Parameter               | Unit   | Value |
|-------------------------|--------|-------|
| Element length          | Mm     | 45    |
| Cross-sectional area    | Mm$^2$ | 17.1  |
| Hydraulic diameter      | Mm     | 1.55  |
| Specific heat capacity  | J·kg$^{-1}$·K$^{-1}$ | 870   |
| Thermal Conductivity    | W·kg$^{-1}$·K$^{-1}$ | 187   |

### 4. Simulation Analysis

#### 4.1. Simulation Analysis of Constant Current Charging Process with Cooling

The heat generation during the fast charging of electric vehicles is concentrated in the constant current stage. Different charging C-rates of 1.0 - 2.5 C-rate are selected for simulation analysis, and the initial temperature of the battery is set to be different. The cooling temperature threshold is selected to be 40°C for cooling, and the cooling system is turned on when the battery temperature reaches 40°C. Turn off the cooling system when it is cooled to 35°C. The highest temperature (HT) and final cooling temperature (FT) of the battery are selected as the research objects, and the simulation results are shown in the Figure 10.

![Figure 10](image-url)

**Figure 10.** Initial temperature and the highest temperature.

Analyzing Figure 19 to Figure 22, it can be seen that when the initial battery temperature of the battery is 25°C and the C-rate is below 1.5 C, the battery temperature is lower than 40°C until the end of charging, and the thermal management system has not been turned on. As the initial temperature increases, and the charging C-rate increases, the highest temperature of the battery increases, and the coincidence point of the highest temperature and the final cooling temperature is delayed as the initial temperature increases. Therefore, the difference in the initial battery temperature affects the maximum acceptable charge C-rate of the battery. Even if the final temperature is cooled to below 40°C, the highest temperature will increase with the increase of the magnification, and the analysis shows that the cooling response capacity decreases with the increase of the magnification.

When the initial battery temperature is 25°C and 30°C, the difference between the highest temperature and the final temperature shows a trend of first increasing and then decreasing. This difference is
affected by two factors: cooling time and charging C-rate influence, when the C-rate is low, the battery temperature drops quickly, and the cooling system is turned off when the temperature drops to 35°C, and the battery temperature starts to increase. Before the lowest point, the battery temperature reaches the threshold for a long time, and the cooling time is very short. As the C-rate increases, the cooling time gradually increases, and the final temperature gradually decreases. After the lowest point, although the cooling time continues to increase, at this time, the charging C-rate plays a leading role. As the C-rate increases, the heat generation of the battery increases, resulting in a gradual increase in its final temperature.

When the initial temperature of the battery is 35 °C and 40 °C, the final temperature shows a trend of first increasing, then decreasing and then increasing. The analysis shows that as the initial temperature increases, the time for the battery temperature to reach the threshold gradually increases. The temperature reaches the cooling stop threshold, the cooling system is closed, the temperature starts to increasing, and as the C-rate increases, the cooling system start and close time gradually advance, and the final temperature gradually increases to the highest value. After reaching the highest value, due to the influence of the charging C-rate, the heating power gradually increases, causing the cooling system to start until the end of charging. The trend at this time is consistent with the above analysis.

Analysis of its highest temperature shows that under different ambient temperatures, as the charging C-rate increases, the highest temperature of the battery gradually increases, and the thermal inertia of the battery becomes larger and larger. When the cooling capacity is sufficient, the cooling response capacity is insufficient, and Threshold cooling has a large limitation on the charging C-rate and cannot fully utilize the performance of the thermal management system. Therefore, when the C-rate is low, the threshold cooling method can meet the cooling needs.

4.2. Research on Cooling Threshold and Cooling Response

For the purpose of improving the cooling response, improvements are made on the basis of the temperature as the threshold. From the perspective of working conditions, there is a big difference between the charging process and the discharging process. The working C-rate of the battery during the discharging process can be affected by many factors such as driving conditions, so it is in an uncertain state, while the C-rate of the constant current charging stage of the charging process is relatively stable. So choose to monitor battery SOC information and temperature, and use SOC as the cooling feedforward signal. Select 25°C, 2.0-2.4 C-rate for simulation experiment, select SOC thresholds as 2.0C-55% SOC, 2.1 C-50% SOC, 2.2 C-40% SOC, 2.3 C-28% SOC, 2.4 C-10% SOC simulation, the results are shown in Figure 11 to Figure 12.

In Figure 11, under different charging C-rates, different SOCs are selected as the feedforward control signals for the cooling system to start, and the highest temperature is controlled at 40°C. Figure 12 compares the difference between the temperature threshold and the highest temperature of the SOC threshold, using temperature as the cooling the highest temperature of the control signal for system startup increases with the increase of the magnification, and the difference from the set 40 °C threshold gradually increases. The SOC control method controls the highest temperature of the battery at 40 °C.
In summary, selecting a suitable control signal for starting the cooling system can eliminate the temperature deviation caused by the response delay, and reduce the battery damage and the risk of thermal runaway caused by excessive temperature.

4.3. Boundary Analysis of Fast Charging Thermal Management

In order to explore the boundary of the charging C-rate, the maximum power cooling analysis of the thermal management during the full charging process is carried out for different ambient temperatures, and the thermal management boundary of the fast charging is explored. During this process, the temperature changes monotonously, and the final temperature is the simulation result as shown in the Figure 13 to Figure 14.

Analyzing the curve in Figure 13, at different initial temperatures of the battery, as the charging C-rate increases, the final temperature increases approximately linearly. Through the simulation calculation of the battery's electric heating model, it can be seen that the average heating power of the battery increases with the increase of the charging C-rate in parabolic upward trend, as shown in Figure 15.

The linear increase in temperature is due to the fact that the charging time of the battery gradually decreases and the increase of the C-rate. The increase of heating power and the shortening of time cause the final temperature of the battery to increase linearly with the C-rate.

In Figure 13, as the initial temperature of the battery increases, the C-rate at which the final temperature of the battery reaches its maximum operating temperature of 40°C gradually advances. As shown in Figure 14, the maximum charge C-rate boundary shrinks linearly. Which limit the charging time. The result provides a basis for the formulation of a fast charging thermal management control strategy.

5. Conclusion

(1) The refrigerant-based direct cooling thermal management system model is built based on the AMESim one-dimensional simulation platform. With the fast charging process of the electric vehicle power battery as the background, during the constant current charging process, the corresponding influence of the battery temperature and the cooling system startup control threshold on the thermal management process And conduct research and analysis on the thermal management boundary of fast charging under the direct cooling system.
(2) Compared with different threshold cooling start methods, the temperature threshold method is suitable for the charging process with low C-rate. As the C-rate increases, the cooling responsiveness decreases. Adding the SOC feedforward control signal can effectively control the highest temperature at 40°C. Below, the problem of poor cooling responsiveness with optimized temperature thresholds.

(3) Through the full cooling of the maximum power of the thermal management system for different charging processes, the thermal management boundary and temperature change law of the charging process are obtained. The results show that the final battery cooling temperature increases linearly with the increase of the charging C-rate, and the maximum charging C-rate decreases linearly with the increase of the ambient temperature.

(4) The above-mentioned thermal management control method and its boundary research are the first research on the thermal management process control of power battery fast charging. On the basis of these conclusions, fuzzy control algorithms can be further introduced for the thermal management system of fast charging process. Perform dynamic control to control the temperature of the battery within an appropriate range under different charging conditions. And in order to explore the temperature field of the battery pack, a three-dimensional battery pack simulation model will be established later to explore and optimize the temperature difference between the inside and outside of the battery pack during the fast charging process. In addition, further research is needed for the low-temperature charging heat management based on the preheating conditions of the direct cooling and heat management system.

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