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Analysis of the Temperature Change of a Single Battery Based on Simulink

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A single battery is the smallest unit of the power source of an electric vehicle. Research on the heat production of a single battery can inform the more precise control the temperature distribution of the entire battery pack. This article selects a certain 18650 lithium-ion battery as the research object. We analyze the working principle, heat production and heat transfer of the battery. Then, we define the basic parameters and establish a heat production model of the single battery. The change in internal resistance of the lithium-ion battery is caused by the state of charge and external temperature. Through its transformation relationship, the impact on the battery temperature is studied. A thermal model of a concentrated mass battery with natural heat dissipation is generated through Simulink to simulate the same temperature at different battery discharge rates and the same battery discharge rate at different temperatures. This method provides a new concept for battery simulation. The temperature increase accelerates at the end of the constant current discharge. When the external temperature increases, the maximum temperature increase of the lithium-ion battery gradually decreases.

Keywords: 18650 battery; Thermal model; Simulink; Temperature; Simulation analysis

1. INTRODUCTION

With the development of automobile technology, electric vehicles are sought after and valued because of their great maneuverability. However, the bulky size of the battery pack, low energy density, proneness to thermal runaway and other issues have become the main constraints for the development of electric vehicles[1,2]. The best working temperature of lithium-ion batteries is 20-40°C. Under the influence of factors such as external temperature and self-heating changes, in real situations, the working temperature of the battery is often higher than ideal. Regulating the working temperature range of the battery pack ensures the safety of electric vehicles, improves the consistency between battery cells and lengthens the battery life. Researchers have conducted in-depth research on battery thermal management from different angles and directions[3,4,5]. Some researchers[6,7] proposed a thermal cycle model based on three-dimensional CFD and a new liquid cooling method for cylindrical batteries. Cold plates are arranged on both sides of the cylindrical battery pack, and the battery cells are connected by an aluminum heat conducting plate. The heat of the battery is transferred to the cold plate through the heat conducting plate. In the case of liquid leakage, the heat conducting plate can function as a separator. Some researchers[8,9] use different materials and different cooling methods to study battery thermal management, and continuously optimize heat dissipation materials and cooling methods to make the battery pack reach suitable conditions. In addition, some scholars conduct research on battery management control strategies[10,11].

Among various studies on batteries, regulating the battery temperature is a very special and important topic. The cooling framework ensures the secure and steady operation of the battery, and the cooling impact of the battery is closely related to battery safety[12]. At present, the commonly used cooling methods are air, liquid and phase change material cooling[13,14]. Compared with the current rich research on battery thermal theory, this article mainly discusses the analysis of the temperature change of a single battery with internal resistance under natural heat dissipation conditions.

Lithium-ion battery has large capacity. Compared with batteries of other materials, electric vehicles are more inclined to choose lithium-ion batteries[15,16,17]. However, temperature affects various aspects of the lithium-ion battery performance, including their capacity, safety, and life cycle. The thermal models of lithium-ion batteries are primarily divided into the following aspects. According to the theory, they can be distinguished into electrochemical-thermal coupling models, electric-thermal coupling models and thermal abuse models. According to the dimensions, they can be divided into concentrated mass models, 1-D models, 2-D models and 3-D modes[18,19].The battery cell in this paper adopts the electrochemical-thermal coupling model according to the principle; the battery cell is considered a mass point according to the dimensions, and the concentrated mass model is used for research.

2. BATTERY PARAMETERS AND SIMULATION

2.1. Working principle and heat production model of lithium-ion batteries

The working principle of lithium-ion batteries is shown in the following chemical reaction equations (1), (2), and (3).

Positive electrode: $$LiMO_2 \rightarrow Li_{1-x}MO_2 + xLi^+ + xe^- \quad (1)$$

Negative electrode: $$nC + xLi^+ + xe^- \rightarrow Li_xMO_2C_n \quad (2)$$

Total response: $$LiMO_2 + nC \rightarrow Li_{1-x}MO_2 + LiC_n \quad (3)$$

During the reaction process of the lithium-ion battery, the heat production model is used to simulate the heat production of the battery, analyze the temperature changes of the battery at various stages, and reduce the development cost and cycle of battery heat dissipation. We establish an electrochemical-thermal coupling model to simulate the chemical reaction and heat conduction characteristics of the battery when the temperature changes.

The actual heat Q_b produced by the lithium-ion battery in the working process continuously increases its own temperature. Formula (4) mainly includes chemical reaction heat Q_r, polarization reaction heat Q_p, ohmic heat Q_j and side reaction heat Q_s.

$$Q_b = Q_r + Q_j + Q_p + Q_s \tag{4}$$

where Q_r is the heat produced during the insertion and extraction of lithium ions when an electrochemical reaction occurs in the battery. The reaction heat calculation formula (5) is as follows:

$$Q_r = \frac{nmQ_eI}{MF} \tag{5}$$

In the formula, n is the total number of batteries; m is the electrode mass, kg; Q_e is the electrode reaction heat, J; I is the current, A; M is the molar mass, g/mol; F is Faraday constant.

Q_j is also called ohmic heating. There is resistance inside the battery, and some heat will be produced when a current passes through it. The calculation formula (6) is as follows:

$$Q_j = I^2R_e \tag{6}$$

where I is the current, A; R_e is the ohmic resistance, Ω.

The polarization heat Q_p is caused by the polarization reaction on the surface of electrodes when the battery is charged and discharged. In the actual calculation process, Q_p is often used to assume that there is a polarized internal resistance R_p and replaced by the produced heat.

The side reaction heat Q_s is the amount of heat that accompanies certain side reactions that occur during the main reaction of the battery.

Battery heat production is difficult to precisely determine in actual situations, and theoretical calculations and experimental tests are more commonly used in engineering. Bernardi[20] considered the battery core as the medium to generate uniform heat and proposed a theoretical calculation model of the heat production rate, which is widely used in the study of thermal models of lithium-ion batteries. When acquiring data for experimental testing, it is necessary to satisfy the adiabatic conditions, i.e., to conduct experiments in an adiabatic environment to ensure the accuracy of the measured battery heat production data. Because it is difficult to realize adiabatic conditions, the accuracy of the experimental data is not high[21,22]. This study mainly adopts theoretical calculation methods, and the widely used heat production rate model formula (7) is calculated and analyzed as follows:

$$P = \frac{dQ_b}{dt} = I[(E_0 - U) - T\frac{dE_0}{dT}] \tag{7}$$

where P is the heating power of the battery, W; Q_b is the heat produced of the battery, J; I is the internal current of the battery, A; U is the working voltage, V; E_0 is the open circuit voltage, V; T is the working temperature of the battery, K (or°C); $\frac{dE_0}{dT}$ is the temperature-affected coefficient of battery voltage, $V \cdot K^{-1}$.

When the number of lithium-ion single batteries is limited, it is usually considered a constant. Because its value is small, it can be ignored[23]. From the literature[24,25], formula (7) can be simplified, and $I(E_0 - U)$ is substituted by the relationship between the current and the total internal resistance.

When the current flows through the resistance, heat is produced and converted into temperature in the battery for storage. The heat production formula in the battery model is simplified into formula (8):

$$P=\frac{dQ_b}{dt}=[I^2R-T\frac{dE_0}{dT}]=I^2R \tag{8}$$

where P is the heating power of the battery, W; Q_b is the produced heat of the battery, J; I is the internal current of the battery, A, and its value is equal to the external current value, which can be measured by an ammeter; R is the total internal resistance of the battery, Ω, and its value is provided in the battery parameters.

During the charging and discharging of the battery, heat is uniformly internally produced, and the specific heat capacity does not change with temperature. Due to the centralized mass model, the thermal conductivity is not considered in this article. When the battery is working, its heat dissipation efficiency should also be considered, and formula (9) is obtained for the heat dissipation rate:

$$\frac{dQ_l}{dt}=hA\Delta T_m \tag{9}$$

where Q_l is the amount of heat exchange, J; A is the surface area of the single battery, m^2; ΔT_m is the difference between battery temperature and external temperature, K (or °C).

Formula (10) for the change in battery heat with temperature is as follows:

$$\frac{dQ_b}{dt}-\frac{dQ_l}{dt}=cm\Delta T \tag{10}$$

where c is the specific heat of the battery, J/(kg·K); m is the mass of the battery, kg; ΔT is the temperature change, K (or°C). In the model, the temperature is controlled by controlling the heat exchange between the battery and the air. For a certain 18650 battery cell, the relevant parameters[26,27]are shown in Table 1.

Table 1. 18650 battery parameters

Parameter	Specification
Dimensions (diameter × height)/mm	18×65
Rated voltage/V	3.7
Mass/g	Approximately 45
Average specific heat capacity/J/(kg·K)	Approximately 1000
Rated Capacity/（A·h）	2.5
working temperature/°C	-20-60
Surface area of the battery/m^2	Approximately 0.045

2.2. SOC and internal resistance of the battery

Fig. 1 shows that the temperature and state of charge (SOC) of the battery have a great effect on the internal resistance of a certain 18650 battery. Under a certain working temperature, the battery internal resistance curve fluctuates between 0.3 and 1 at the state of charge, but the overall stability is relatively constant , the difference in internal resistance changes is not significant, and the SOC hardly affects the internal resistance of the battery. When the SOC is less than 0.3, as the SOC decreases, the internal resistance curve rapidly increases, the internal resistance rapidly increases, and the heat production increases. At this time, the power performance of the battery rapidly decreases. Therefore, when driving an electric vehicle, one should charge the battery in time when the battery power is low, and the SOC should be maintained above 0.3 as much as possible to avoid continuous work when the battery is low, which reduces its performance.

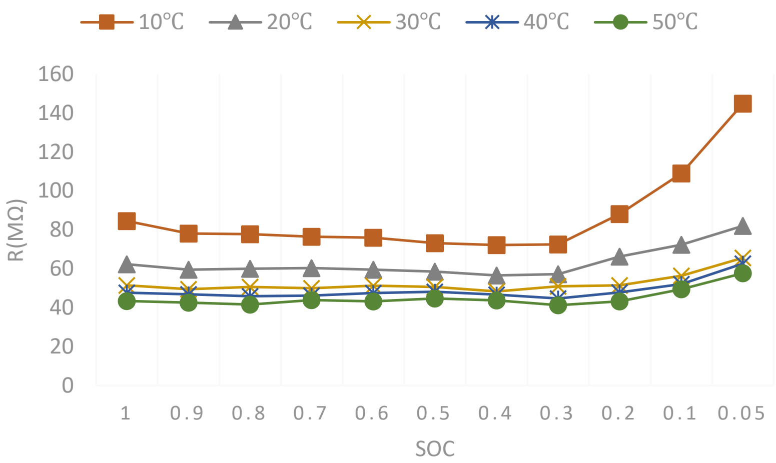


Figure 1. Transformation of internal resistance at different temperatures and SOC states.

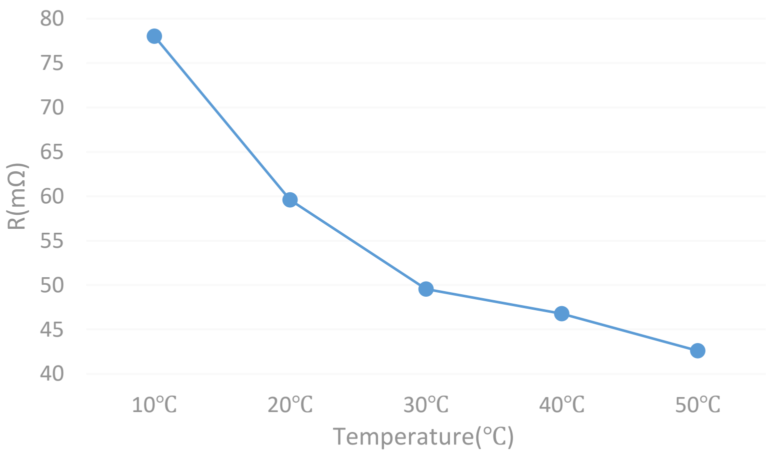


Figure 2. Internal resistance change curve with temperature.

Fig. 2 shows the change curve of the battery internal resistance with temperature when the SOC is 0.9. Temperature has a significant influence on the internal resistance of the battery. At a constant SOC, when the external environment temperature decreases, the internal resistance of the battery increases. The difference in internal resistance at 30°C, 40°C and 50°C is small, the difference in internal resistance becomes larger at 20°C, and the change in internal resistance is obvious at 10°C, which significantly increases. The reason is that when the temperature is low, the electrochemical reaction rate inside the battery decreases, which increases the polarization phenomenon, and the internal resistance significantly increases. Low temperature will seriously influence the battery capacity, performance, etc., so one should avoid operating the battery in a low-temperature environment as much as possible.

The total internal resistance of the lithium-ion battery continues to decrease when the external temperature increases because the activity of lithium ions is relatively low at low temperature, the concentration in the electrolyte increases, and the movement speed of ions in the electrolyte decreases. The slow chemical reaction increases the internal resistance of the battery. When the temperature increases, the chemical reaction in the battery changes from slow to fast, lithium ions move faster, and the internal resistance of the battery decreases. However, if the battery is overheated, the internal electrolyte of the battery will decompose, and the chemical reaction will be violent. Simultaneously, it will aggravate the aging of the electrode structure and reduce the service life.

However, compared to increasing the temperature from 10℃ to 30℃, when the temperature is increased from 30℃ to 50℃, the decrease in internal resistance of the lithium-ion battery will be significantly reduced. Fig. 2 also shows that the internal resistance changes with temperature, and it is not a linear relationship. When the temperature is 10-30℃, the resistance greatly changes, and the curve is steeper. The reason is that at this temperature, the lithium-ion battery gradually increases from a low temperature environment to the best working temperature environment, and the resistance greatly decreases when the temperature increases. When the temperature is increased from 30℃ to 50℃, the resistance change is relatively small, and the curve is relatively slow because the lithium-ion battery changes from the best working temperature environment to the high temperature environment. When the temperature reaches a particular value, the lithium ion movement speed decreases, and the resistance change also decreases.

2.3. Model development

After analyzing the mathematical model of the lithium-ion battery, according to its thermophysical parameters and heat production and heat transfer characteristics, we used Simulink to build the heat production model, as shown in Fig. 3.

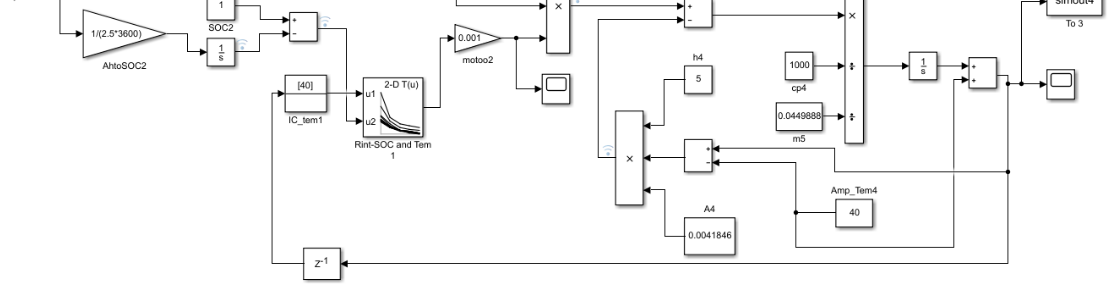


Figure 3. Battery thermal model based on Simulink.

This article studies the constant-rate discharge of lithium-ion batteries. According to the calculation method of SOC over time proposed by K.W.E. Cheng[28] during constant-rate discharge, the SOC calculation formula (11) is as follows:

$$SOC_1 = SOC_0 - \Delta SOC = SOC_0 - \frac{It}{3600C_R} \tag{11}$$

In the formula, SOC_1 is the remaining SOC value of the battery; SOC_0 is the SOC value of the battery at the beginning; ΔSOC is the consumed SOC value of the battery during the discharge process; I is the current, A; t is the discharge time, s; C_R is the rated capacity of the battery.

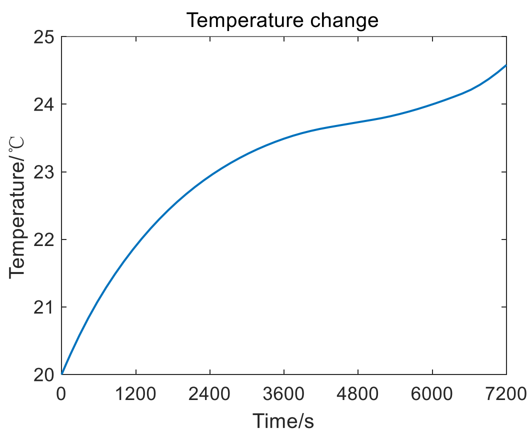
$$P = I^2 R = I^2 \cdot f(T,t) \tag{12}$$

When performing thermal simulation analysis on a lithium-ion battery in Simulink, according to the heat production formula of the lithium-ion battery, the battery does have not a constant calorific value but is a dynamic heat source, which changes with the battery discharge rate, SOC and temperature.

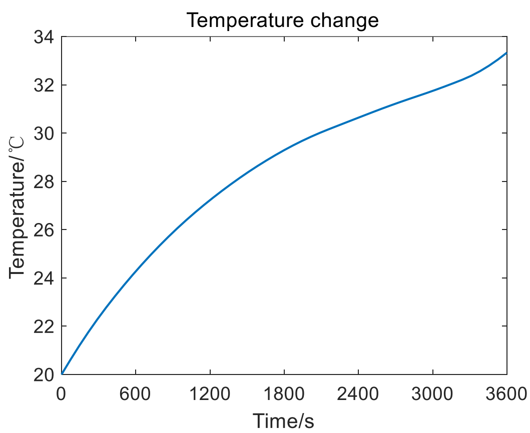
3. RESULTS AND DISCUSSION

3.1 Battery temperature rise under different discharge rates

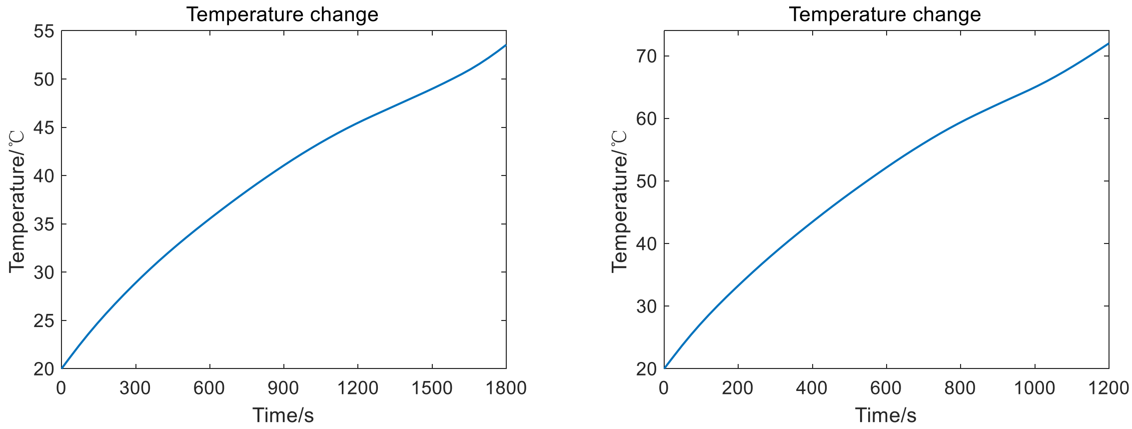
To achieve practical temperature changes during battery discharge, the battery external temperature is set to 20℃, and convection heat transfer is considered natural convection. According to experience, the convective heat transfer coefficient is determined to be 5 W/(m^2·K). A lithium-ion battery produces a large amount of heat during the discharge process, which makes the battery temperature increase, and the discharge rate has an important impact on the heat production and temperature of lithium-ion batteries. The temperature changes of a single cell at 0.5-C, 1-C, 2-C and 3-C rate discharges are obtained by simulation. Fig. 4 shows the average temperature change curves of the battery when it is discharged at 0.5-C, 1-C, 2-C, and 3-C rates.



(a)0.5C



(b)1C



(c)2C (d)3C

Figure 4. Battery temperature curves under different discharge rates.

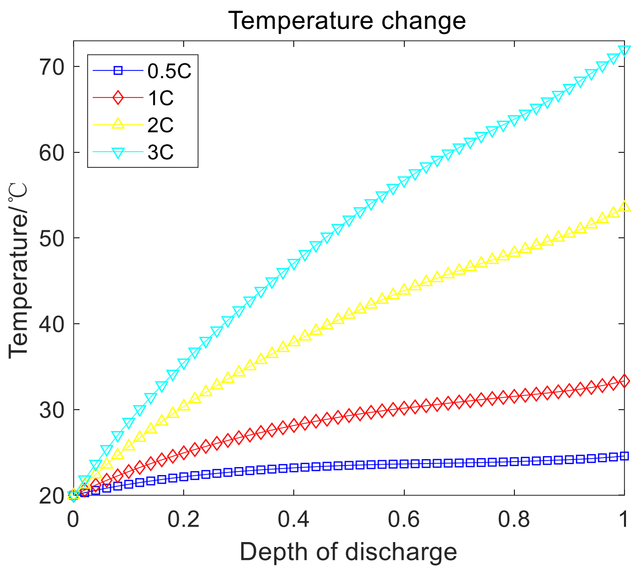
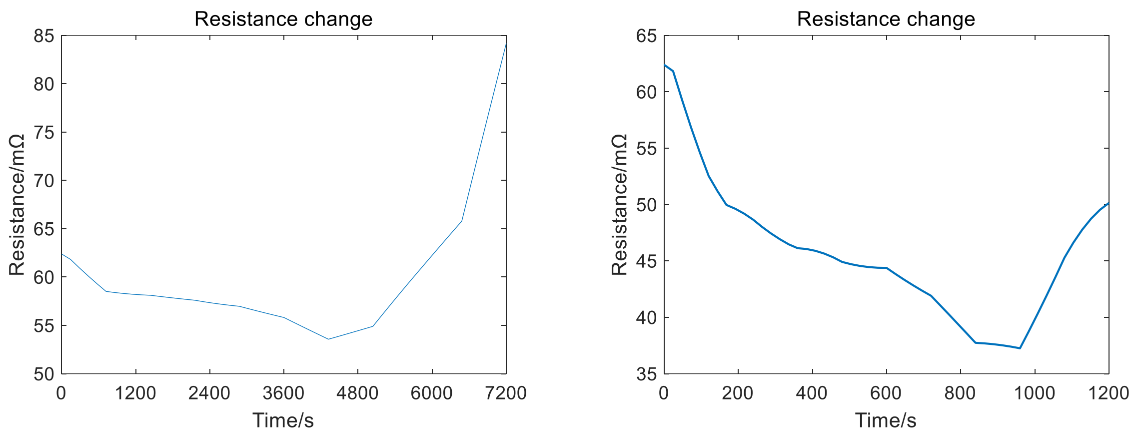


Figure 5. Summary of battery temperature curves under different discharge rates.

The depth of discharge (DOD) is the percentage of the discharge capacity to the rated capacity. When the depth of discharge is 0, the SOC value is 1, which shows that there is no discharge behavior at this time. When the depth of discharge is 1, the SOC value is 0, which indicates that the discharge is complete at this time, and the battery power is 0. For example, if the battery is discharged at 1C and the duration is 3600 s, the corresponding depth of discharge is 1, and the other discharge rates can be deduced by analogy. The temperature curves in Fig. 4 and Fig. 5 show that when the external temperature is 20℃, as the discharge rate increases, the battery temperature rapidly increases. The formula of the heat production rate shows that the square of the discharge current is proportional to the battery heat production rate. When the current increases, more heat is produced[29]. When discharging at 0.5C, the overall temperature of the battery slowly increases. In the later stage of discharge, the average temperature of the battery increases by approximately 4.6℃ to reach 24.6℃. When the battery is discharged at 1 C, the battery temperature rapidly increases; in the later stage of the discharge, the battery temperature increases by approximately 13.3℃[30]. When the battery is discharged at 2C, the fluctuation range of the battery temperature curve is reduced, and the battery temperature always increases throughout the discharge process. In the later stage of the discharge, the average battery temperature increases by approximately 23.5℃. When the battery is discharged at 3 C, the battery temperature curve basically tends to linearly change, and the average temperature of the battery increases by approximately 52℃ at the end of the final discharge.



(a)0.5C (b)3C

Figure 6. Change in internal resistance with time under 0.5-C and 3-C discharge rates.

From Fig. 4 and Fig. 5, the temperature change curves of the discharge rate under four different working conditions are compared, and the temperature increases more quickly at the end of the constant-rate discharge. Fig. 2 shows that when the SOC of the battery is lower than 0.3, the internal resistance will gradually increase with the decrease in SOC, so the heat production of the battery increases in the later stage of the discharge. The temperature continues to rise, and the heat production is higher than that in the previous situation. The curve change at 0.5-C discharge greatly fluctuates. When discharging at a small rate of 0.5 C, the current is small, the heat production rate of the battery is low, the overall temperature of the battery gradually stabilizes, and the temperature slowly rises[31,32]. However, the middle part of the temperature curve becomes flat. Fig. 6 shows that this flattening occurs because when the discharge time continues, when the SOC is in the middle section, the internal resistance of the battery is minimal, and the heat production is small. For the 3-C high-rate discharge, the overall curve is flat. although the resistance decreases in the middle of the discharge, due to the high-rate discharge, the SOC quickly decays to below 0.3 at this stage, the internal resistance increases, and the heat production rapidly increases.

3.2 Battery temperature rise at different temperatures

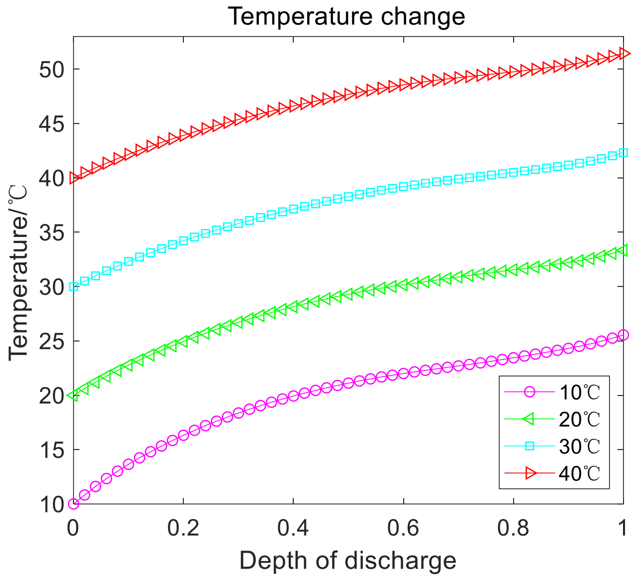


Figure 7. Summary of battery temperature curves of the 1-C discharge rate at different temperatures.

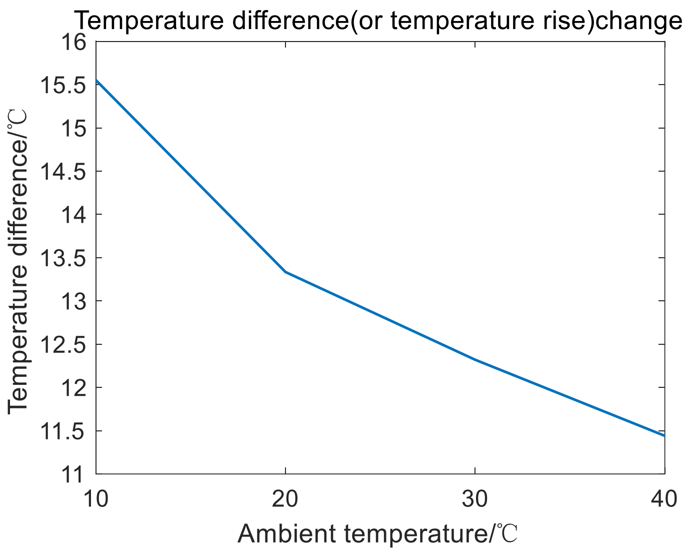


Figure 8. Curve of the temperature difference (or temperature rise) at different temperatures.

From Fig. 7 and Fig. 8, the discharge rate is 1 C. When the external temperature is 10°C, 20°C, 30°C, and 40°C, the highest temperature increase at the end of the discharge is approximately 15.5°C, 13.3°C, 12.3°C and 11.4 °C. Under these four different external temperatures, the maximum temperature difference gradually increases when the external temperature decreases because the decrease in temperature causes a gradual increase in internal resistance of the battery, which eventually causes an increase in heat from the battery[33]. Under a low-temperature environment, the change in internal resistance is particularly obvious.

4. CONCLUSION

This paper concisely presents the fundamental theory of lithium-ion battery cells and their thermal characteristics; then, it simulates and analyzes this type of single battery. According to the heat production mechanism of lithium-ion batteries, the Bernardi heat production rate calculation model has been simplified to only consider the heat produced by the battery current that flows through the total internal resistance. A simulation model was built based on Simulink. Through the internal resistance and temperature change of the single battery, the influence of SOC and temperature on the internal resistance of the battery and the influence of the discharge rate on the temperature change of the battery were studied and analyzed.

The results show that when the temperature is constant, the internal resistance of the lithium-ion battery does not greatly change in the SOC range of 0.3-1, and the internal resistance decreases in a small range. When the SOC is less than 0.3, the internal resistance increases when the SOC decreases. In the later stage of discharge, the internal resistance of the battery rapidly increases. When the SOC is a regular value, the internal resistance of the battery increases when the temperature decreases with an exponential trend. The temperature change curve of the battery under different working conditions shows that the temperature rises faster than before in the later stage of the constant-rate discharge. Under the same discharge rate, because of the drop in temperature in the environment, the maximum temperature increase and temperature difference of the model will increase.

Cooling by natural convection heat dissipation occurs at an external temperature of 20℃. At lower discharge rates such as 0.5C and 1C, the battery remains at the ideal working temperature, and other heat dissipation methods may not be required. Under high-rate discharge conditions such as 2 C and 3 C, the battery generates serious heat, and the natural heat dissipation method can no longer fully satisfy the normal working temperature state of lithium-ion batteries. With increasing discharge rate, the battery temperature increases, and it is necessary to adopt a reasonable and effective battery heat dissipation method.

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