Exploration of Thermal Management Issues in the Battery Life Cycle

Qiyu Yang1,2,* and Jialiang Wang1,2
1State Key Laboratory of Automotive Simulation and Control, Jilin University, Changchun 130022, China
2College of Automotive Engineering, Jilin University, Changchun 130022, China

*Corresponding author email: yangqy18@mails.jlu.edu.cn

Abstract. In order to comprehensively track and monitor battery performance across time domains and perform efficient thermal management. This article first summarized the research progress and status quo of battery aging models, and then coupled it with thermoelectric models to obtain the evolution of battery characteristic parameters during battery decay. From the perspective of the battery life cycle, it explored the thermal safety control and overheating prevention technology of power batteries, proposed a feed-forward heat management strategy, and took cooling measures in advance to prevent the increase in heat production caused by aging. The results show that the feed-forward thermal management strategy can ensure the cooling effect of the cooling system on the battery in the later stage of aging.

Keywords: Electric vehicles; Battery thermal management; Aging.

1. Introduction

The research on thermal management of battery life cycle is mainly divided into two aspects. One is the need to clarify the aging of the battery and its impact on the battery. The other is to take corresponding thermal management measures on the basis of aging research to alleviate battery aging and improve battery life. There are still many problems related to this research: (1) The research of aging mechanism involves a variety of materials and a variety of physical and chemical reactions, and there are many difficulties in analyzing the reaction mechanism. Relevant scholars have done a lot of research. Victor Agubra et al. [1] conducted a research summary on the aging of lithium-ion batteries and its degradation mechanism, including lithium evolution, SEI film formation, irreversible lithium ion loss, graphite particle exfoliation and other structural changes. The optimization and improvement of the negative electrode of the battery are proposed as a method reference. (2) The battery aging model involves the coupling relationship between multiple factors. There are many factors that affect aging, and the influence between the factors is not clear, which brings difficulties to the establishment of a suitable model. Yunjian Li [2] researched and established a battery model, which includes an RC equivalent circuit model, a thermal model and a semi-empirical battery aging model. The three sub-models are coupled to form an electrothermal-aging model. The electrical parameters in the model are related to battery temperature and current, and the thermal parameters are related to voltage, current and external convective heat transfer coefficient. The parameters of the aging model depend on the current and battery temperature. These sub-models are interrelated and affect each other. (3) Thermal management measures should not only consider the cooling effect and the prevention and control of thermal runaway, but also the energy saving of the system. Rui Zhao et al. [3] developed a heat pipe-humid-cooling combination battery thermal management system. This system is distributed between
chip batteries and heat pipes. The length of the heat pipe is slightly longer than the battery. The extension part of the heat pipe exchanges heat through liquid spray. Compared with the air cooling method, this method not only improves the temperature drop and temperature uniformity, but also reduces the system quality. The following will summarize the current research progress from three perspectives of aging mechanism, aging model and thermal management measures.

2. Battery Aging Mechanism
During the battery’s use, macroscopic external factors such as temperature, SOC (State of charge), discharge rate, and mechanical stress will affect its aging process. The reflection in the battery is generally the irreversible reaction on the positive and negative electrodes, the decomposition of the electrolytic liquid, the decomposition of the binder, and the corrosion of the current collector. Vetter J et al. [4] summarized the aging mechanism of lithium-ion batteries, systematically classified the aging of the lithium metal oxide positive electrode and carbide negative electrode of the battery, and analyzed various reasons for the decline of carbon-based negative electrodes and their effects on the battery. Finally, the basic aging mechanisms of the two types of cathode materials under different cycles and storage conditions are summarized and compared. On this basis, Bin Pan et al. [5] further divided the potential capacity degradation modes of lithium-ion batteries into LLI (lithium ion loss) and LAM (lithium ion active material loss) when analyzing the aging mode of lithium batteries, simplifying a variety of complex aging mechanisms.

In addition, there are many detailed studies on the aging mechanism of the electrodes. Among them, the changes in the SEI (solid electrolyte interphase) film, lithium evolution, irreversible lithium ion loss, and graphite particles peeling and cracking occur frequently in the negative electrode part. Most scholars focus on the formation and growth of SEI, because it has the greatest effect on battery aging. The degradation of the battery cathode is mainly divided into three parts: structural changes in the cycle, chemical decomposition on the anode, and surface film modification [1]. Broussely M [6] and others to improve the purity of the material by means of reducing the gas decomposition reaction of the positive electrode, extend the life expectancy, optimizing proved positive electrode material delaying aging. The reaction of other parts of the battery mainly occurs on inert materials, including the corrosion of the current collector, the oxidation of the conductive agent and the decomposition of the binder, and the decomposition of the electrolyte to produce gas. These side reactions will not only reduce the mechanical stability of the battery, but also cause contact loss between various active materials. The diaphragm acts as a channel for ions in the electrolyte, and its porosity changes will affect the ion passage rate, thereby affecting the battery capacity [7].

From the perspective of research methods to explore battery aging mechanism, in recent years, in-situ testing technology and external characteristic analysis technology have been widely used in the research of analyzing battery aging mechanism. Because the two do not need to disassemble the battery cells, the changes in battery aging over time can be studied in real time. Koltypin M et al. [9] used in-situ atomic force microscopy (AFM) to study the morphological changes in composite graphite electrodes. Not only was the passivation surface film formed on the surface of the graphite electrode reacted with the electrolyte, but it was also found that the volume of graphite particles would increase during the insertion-deintercalation process of lithium, resulting in a slight change in electrode morphology. This slight change in the electrode increased the deposition of reactants on the surface film, resulting in the deterioration of the graphite electrode and the reduction of battery capacity.

The typical method of external characteristic analysis technology is IC (incremental capacity analysis) curve, DV (differential voltage analysis) curve analysis method. The advantage of these methods is to convert the voltage plateau on the voltage curve into identifiable differential peaks. These differential peaks are related to the phase change phenomenon during the Li⁺ insertion/de-embedding process of the electrode. Han X et al. used these two methods to analyze the aging mechanism of batteries. According to the reproduction of the IC curve, DV curve and charging voltage curve at 25°C with 1/3 C constant current charging curve, the aging mechanism of five commercial batteries participating in test is analyzed, and the aging mechanism of these batteries is compared [9].
Based on the research and analysis of the above-mentioned aging mechanism, SEI film and the side reaction of lithium evolution are the factors that have a relatively large impact on battery aging. However, the internal chemical structure of the battery is complex, various reactions affect each other, and the external conditions are also diverse, so it is difficult to quantitatively study battery aging from the perspective of mechanism. It is mainly to establish a battery aging model through various analytical methods, and on this basis to predict, supervise and calculate and analyze the battery aging process. Table 1 shows some research results on the location of the aging of lithium-ion batteries and the internal mechanism.

Table 1. Lithium ion battery aging mechanism.

| Reaction parts | Reaction type                                      |
|---------------|---------------------------------------------------|
| negative electrode | Metal dissolution          |
|                | Volume expansion and porosity increase            |
|                | Graphite exfoliation                              |
|                | Decomposition and growth of SEI film              |
|                | lithium plating                                  |
|                | Structural changes in the loop                    |
| positive electrode | Dissolution reaction                             |
|                | Electrode particle cracking                       |
|                | Surface film modification                         |
|                | Corrosion of collector plate                      |
| Other parts   | Oxidation of conductive agent                     |
|               | Decomposition of adhesive                        |
|               | Electrolyte decomposition                         |
|               | Change of diaphragm porosity                      |

3. Aging Model

The establishment of the aging model can effectively predict the physical and chemical state of the battery during operation, and it can also describe the dynamic behavior of heat generation and discharge through the model equations. This is the basis for the study of battery aging and battery management research. On the one hand, the heat production law of the battery will change with the cycle aging and calendar aging process. On the other hand, the heat production change of the battery will also affect the temperature distribution of the battery cell and the whole package, and then affect the temperature-related parameter values, which changes the process of battery aging. These factors will increase the difficulty of modeling. Therefore, the establishment of a battery model throughout its life cycle is important in the study of aging and thermal management.

3.1. Mechanism Aging Model

The electrochemical mechanism model of the battery is mainly divided into SP (single particle) model and P2D (pseudo two-dimensional) model. The P2D model developed by Doyle et al. is based on porous electrode theory and concentrated solution theory, and can simulate the physical and chemical processes inside the battery through the establishment of model equations \(^{[10]}\). Commonly used battery electrochemical models mainly include the governing equations and boundary condition equations of the electrolyte phase and solid phase of lithium batteries based on the Newman model equations. The governing equation describes the mass transfer and charge transfer process of lithium ions in the electrolyte phase and the solid phase \(^{[11]}\). The charge conservation formula of the electrolyte phase of lithium ion batteries is as follows:

\[
\nabla \cdot \left( \kappa_e^{\text{eff}} \nabla \varphi_e \right) + \nabla \cdot \left[ \kappa_{e,\text{D}}^{\text{eff}} \nabla \ln (c_e) \right] = -a_e \left( j + j_s \right)
\]
On the basis of the phase equilibrium model, a kinetic model based on the P2D governing equation defines the kinetic expression of the lithium ion intercalation reaction and the solvent reduction reaction\(^{[12]}\), in which the current density equation of the lithium ion intercalation reaction is as follows:

\[
\frac{\partial \varphi_i}{\partial x} \bigg|_{x=0} = \frac{\partial \varphi_i}{\partial x} \bigg|_{x=L} = 0
\]

(2)

And C. Edouard et al. integrated the aging mechanism model of the porosity change caused by the growth of the SEI film. The model includes equilibrium equations and boundary condition equations, describing the SEI growth mechanism of solvent diffusion during aging\(^{[13]}\). The SEI film growth rate equation is as follows:

\[
\frac{d\delta_{\text{SEI}}}{dt} = -\frac{i_s M_{\text{sei}}}{2 F \rho_{\text{sei}}}
\]

(4)

Safari, M et al. used a single particle (SP) model for aging simulation. The aging model is also based on the decomposition reaction on the SEI film to describe the process of capacity decay, and can simulate the cyclic aging and calendar aging curves of various batteries. The single-particle model is relatively simplified and can save a lot of calculation time, but the model does not consider the transport of the electrolyte phase, and the accuracy is low at high discharge rates\(^{[14]}\). The side reaction current density equation of the negative electrode in the aging model is as follows:

\[
i_s = a_j i_{0,j} \left[ \exp \left( \frac{a_{i,j} F}{RT} \eta_j \right) - \exp \left( -\frac{a_{i,j} F}{RT} \eta_j \right) \right]
\]

(3)

On the basis of some commonly used aging mechanism models, many researchers have also made innovations and explorations. T.R. Ashwin et al. established a new P2D model. This model simplifies the electrochemical parameters in the theoretical model based on porous point poles, adopts implicit formulas instead of traditional linear equations, reduces the calculation requirements, and also maintains the accuracy of predictive calculations \(^{[11]}\). Shriram Santhanagopalan et al. \(^{[15]}\) discussed the advantages and disadvantages of the simplified model in predicting aging and simulating capacity degradation. The results show that the simplified model can not only greatly reduce the calculation time, but also the calculation error is within an acceptable range. However, the limitation of the SP model is that there is a lack of accuracy at a discharge rate higher than 1 C. Different aging mechanism models often have different modeling ideas, but also have relatively high accuracy, involving the relevant knowledge details of physical and chemical reactions. Therefore, the accuracy of the mechanism model can reach a high level. However, the complexity of modeling and the coupling of multiple parameters also make the verification of the model more difficult, and there are also high requirements for the theoretical knowledge of the developer.

3.2. Empirical Aging Model

The establishment of empirical models does not require in-depth research on a large number of electrochemical reaction processes, with fewer parameters and simpler models. However an empirical summary must be made on the basis of multi-condition research of cyclic aging and calendar aging tests. For the cyclic aging model, P. Ramadass et al. \(^{[16]}\) established the aging empirical formula for the capacity attenuation related parameters. The formula uses the number of cycles to characterize the changes in the three parameters of charge state, membrane resistance and solid phase diffusion coefficient, and develop a capacity decay prediction model based on this. The model uses the loss of active substances as the basis for modeling, and on this basis adds the consideration of rate capability loss. John Wang et al. \(^{[17]}\) established a cyclic aging model for lithium iron phosphate batteries. This
model studies the influence of time, temperature, depth of discharge and discharge rate on capacity decay. The results show that time and temperature have a relatively large impact on capacity, while at low discharge rates, the impact of discharge depth is weak. The development of this model is based on the power law model, and different power law factors are adopted for the formulas under different discharge rates. The calculation results of the model are verified by experiments, and the error is within the allowable range, but the error is slightly larger under high discharge rate.

Many scholars have also conducted related research on the calendar experience aging model. I Bloom et al. [18] studied the calendar aging of batteries and established an aging model. Experimental results show that battery life is affected by temperature, time and SOC, of which temperature and time are the main factors. The calculation results of the model are very close to the experimental data. Madeleine Ecke et al. [19] studied the dynamic interaction between the thermal, electrical and aging behavior of the battery. The calendar aging model is obtained to predict the battery aging under different working conditions. This empirical model describes the effects of temperature and charge state on impedance rise and capacitance decay, and simultaneously introduces thermal and electrical parameters into the aging model equation.

Different from the above model, Johannes Schmalstieg et al. [20] established an empirical model of calendar aging and cyclic aging. The cycle capacity loss and resistance increase are characterized as a function of the aging coefficient, the number of days and the amount of charge passed, and it is suitable for both standing and cycling conditions. The establishment of the aging model has undergone many experimental tests of calendar aging and cyclic aging.

This modeling method reduces the user's requirements for theoretical knowledge of electrochemical mechanisms, and can easily establish the relationship between battery operating parameters and experimental characteristics. The limitation of the empirical model is that it cannot be applied to a variety of batteries of different material types, and the acquisition of a large amount of experimental data requires a long time period. Table 2 shows the empirical aging formula mentioned above.

The aging models of batteries are divided into electrochemical mechanism models and empirical models. The limitation of the electrochemical model is that it can only describe the aging phenomenon inside a specific type of battery, and cannot be extended to other batteries. Not only that, the electrochemical mechanism model contains too many chemical reactions and covers many electrochemical parameters. The calculation is very complicated and it is difficult to verify the model. The semi-empirical model captures the main factors in the mechanism model, with fewer parameters and simple calculations, but at the same time it reduces the accuracy of the model. Empirical models are more based on empirical formulas, parameters and models are more simplified than mechanism models. It does not rely on the related mechanism of aging, but requires a lot of experimental data to apply to the model formula.

3.3. Thermoelectric-aging Coupling Model

The thermal and electrical models of the battery are related and coupled with each other, and there will be dynamic interactions between the electrical and thermal behaviors. The electrical parameters of the battery will directly affect the heating power of the battery, change the calorific value, thus change the temperature of the battery, and affect the thermal parameters. Similarly, when the temperature of the battery changes, the resistance will also change, which affects many electrical parameters.

The establishment of the aging model of the battery is also inseparable from the thermoelectric model. Important parameters of battery aging will affect the capacity decay and impedance increase of the battery. Couple the thermoelectric model and the aging model together to explore the dynamic interaction between heat, electricity and aging behavior. Figure 1 shows the coupling relationship diagram of the thermoelectric-aging model.
### Table 2. Empirical model of aging.

| Empirical equation | Cyclic aging | Cycle aging battery capacity attenuation model\[17\] | Calendar aging | Comprehensive model |
|--------------------|-------------|-------------------------------------------------|-----------------|---------------------|
| Cycle aging capacity loss changes with the number of cycles\[16\] | \(-d\theta dN = k_3N + k_4\) \(\text{initially} \theta = \theta^0(T)\) | \(Q_{\text{loss}} = B \cdot \exp\left(\frac{-E_a}{RT}\right) t^z\) | \(Q = A\exp\left(-\frac{E_a}{RT}\right) t^z\) | \(C = 1 - \alpha_{\text{cap}} \cdot t^{0.75} - \beta_{\text{cap}} \cdot \sqrt{Q}\) |
| Cycle aging battery capacity attenuation model\[17\] | \(L_{\text{cap}}(t,T,V) = L_{\text{cap}}(t_0,T,V) \cdot \left[1 + B(T,V) \cdot F(t)\right]\) | \(F(t) = c_{\alpha} \cdot t^{\beta}\) | \(R = 1 + \alpha_{\text{res}} \cdot t^{0.75} + \beta_{\text{res}} \cdot Q\) | \(\alpha_{\text{cap}}(T,V) = \left(7.543 \cdot V - 23.75\right) \cdot 10^5 \cdot e^{-\frac{6976}{T}}\) |
| Calendar aging model\[19\] | \(B(T,V) = c_{\alpha} \cdot e^{\frac{LTV - LTV_0}{MT}}\) | \(\alpha_{\text{res}}(T,V) = \left(5.270 \cdot V - 16.32\right) \cdot 10^5 \cdot e^{-\frac{5986}{T}}\) | \(\alpha_{\text{cap}}(T,V) = \left(7.543 \cdot V - 23.75\right) \cdot 10^5 \cdot e^{-\frac{6976}{T}}\) | \(\alpha_{\text{cap}}(T,V) = \left(7.543 \cdot V - 23.75\right) \cdot 10^5 \cdot e^{-\frac{6976}{T}}\) |
| Total aging function integrating calendar aging and cycle aging\[20\] | \(\alpha_{\text{cap}}(T,V) = \left(7.543 \cdot V - 23.75\right) \cdot 10^5 \cdot e^{-\frac{6976}{T}}\) | \(\beta_{\text{res}} = 2.153 \cdot 10^{-4} \cdot (\emptyset V - 3.725)^2 - 1.521 \cdot 10^{-5}\) | \(\beta_{\text{res}} = 2.153 \cdot 10^{-4} \cdot (\emptyset V - 3.725)^2 - 1.521 \cdot 10^{-5}\) | \(+2.798 \cdot 10^{-4} \cdot \Delta DOD\) |
| Comprehensive model | \(\beta_{\text{cap}} = 7.348 \cdot 10^{-3} \cdot (\emptyset V - 3.667)^2 - 7.600 \cdot 10^{-4}\) | \(\beta_{\text{cap}} = 7.348 \cdot 10^{-3} \cdot (\emptyset V - 3.667)^2 - 7.600 \cdot 10^{-4}\) | \(\beta_{\text{cap}} = 7.348 \cdot 10^{-3} \cdot (\emptyset V - 3.667)^2 - 7.600 \cdot 10^{-4}\) | \(+4.081 \cdot 10^{-3} \cdot \Delta DOD\) |
Many scholars have established thermoelectric-aging coupling models from different angles. Yunjian Li et al. \cite{2} found that as the battery ages, it is important to ensure the accuracy of SOC estimation. For this, they developed a variable time domain modeling method that combines offline prediction and online capacity parameter estimation. Different fitting functions are used to quantify the relationship between model parameters and the number of cycles, thereby establishing a more accurate coupling model, which can improve the accuracy of SOC prediction in different cycle intervals. Guiwen Jiang et al. \cite{21} established a coupling model to study the uneven distribution of battery heat. This modeling not only considers the dynamic relationship between thermal, electrical, and aging parameters, but also refines the calculation of heat transfer inside the battery and improves the accuracy of the model. Jaeshin Yi et al. \cite{22} expressed the key parameters as a function of changing the number of cycles in the modeling process, and proceeded with the two Dimensional modeling. It can help to propose strategies to improve battery pack control, thereby improving battery life and operating performance.

4. Thermal Management Measures

Power batteries are the core components of electric vehicles, which provide energy for the operation of electric vehicles, and also account for a large proportion of the overall cost of electric vehicles. In the battery pack of an electric vehicle, the arrangement is very compact. The battery pack generates a lot of heat during charging and operation. If the heat dissipation and cooling measures are not complete, the temperature is too high will produce heat out of control, causing safety accidents. Even if it does not reach the level of thermal runaway, unsuitable temperatures will aggravate the aging of the battery pack. Thomas Waldmann et al. \cite{23} explained the necessity of thermal management measures from the perspective of battery aging mechanism. Under different fixed temperature conditions from -20 °C to 70 °C, a 1 C charge-discharge rate cycle is used to perform a cycle experiment on 18650 lithium ion batteries. The results show that the battery ages the slowest at a temperature of 25 °C. The lithium plating of the anode at low temperature and the dissolution of the electrolyte interface and the anode at high temperature will accelerate the aging.

It can be seen that when the temperature difference in the battery pack is large, the variability of the electrochemical reaction will increase and the output efficiency of electric energy will decrease. Due to the "barrel effect", excessive differences will also reduce the life of the overall battery pack and affect the stability of the overall battery pack. How to control the temperature of the battery pack in the best state, and the overall balance is controllable, is the main research direction of current thermal management to delay aging. At present, many scholars have designed a new type of thermal management system to further reduce the maximum temperature of the battery pack and improve the temperature uniformity of the battery pack. In addition to considering the cooling effect of the cooling system, the power consumption of the system and the lightweight of the entire thermal management system also need to be considered.

According to the different heat exchange media in the thermal management system, currently, the widely used cooling systems can be divided into two categories: air cooling and liquid cooling. The
advantages and disadvantages are different, and the researchers optimized these cooling methods accordingly. Rajib Mahamud et al. [24] adopted a battery thermal management system with reciprocating airflow. Numerical analysis results show that the reciprocating flow improves the temperature uniformity and temperature drop of the battery, and the shorter the reciprocating time, the better the temperature uniformity and temperature drop of the battery. When the reciprocating flow cycle reaches $\tau = 120$ s, the reciprocating flow can reduce the maximum temperature of the battery by 1.5 °C compared with the unidirectional flow. This also shows that proper optimization of thermal management measures significantly improves battery temperature control.

Compared with air cooling, the cooling medium of liquid cooling system has a higher heat transfer coefficient, and related research is also very abundant. Haitao Wang et al. [25] found that in the liquid-cooled heat management system, there is a flow threshold to increase the flow rate to reduce the maximum battery temperature and improve the temperature uniformity. When the flow reaches a certain value, the optimization of temperature drop and temperature uniformity will gradually slow down, and higher power consumption can only achieve a smaller optimization effect. Joshua Smith et al. [26] compared the calculation results of 2D and 3D CFD (Computational Fluid Dynamics) simulation models in liquid cooling systems. Using 3D surface map and 2D contour map, the influence of inlet flow rate and inlet temperature on battery temperature difference and maximum temperature was explored. The results show that the decrease of the maximum temperature of the battery pack is accompanied by a certain loss of temperature uniformity.

The direct cooling battery thermal management is a kind of liquid cooling method. This cooling method uses the evaporator in the air-conditioning system as the cold plate, and the refrigerant in the air-conditioning system circuit as the cooling medium, and directly uses the latent heat of the refrigerant boiling phase change to cool the battery. Compared with the traditional liquid cooling method, the direct cooling system has a higher heat exchange coefficient, higher cooling efficiency and a more compact structure. Yan-Feng Wang et al. [27] studied the heat transfer phenomenon of refrigerant HFE-7000 flowing and boiling in a DC (direct cooling) tube and came to the following conclusion: the maximum temperature of the battery pack is inversely proportional to the refrigerant flow rate; it affects the temperature drop of the battery pack The main factor of performance is the forced convection heat transfer between the refrigerant and the cold plate; the dominant factor of temperature homogeneity is the nucleate boiling heat transfer of the refrigerant. The refrigerant flows and boils in the tube, which reduces the contact thermal resistance, optimizes the heat transfer process, and greatly improves the temperature uniformity and temperature drop of the battery pack.

In addition to effective temperature control, energy-saving optimization can also extend battery pack life. If the optimization of temperature control methods leads to a negative increase in battery life, the result of thermal management measures will be lost. Gross Oliver and Clark Steven [28], based on the establishment of a battery calendar cycle aging model, explored the net positive impact of battery thermal management measures for pure electric vehicles on battery life. The battery thermal management system consumes battery energy during recycling. For example, for a pure electric vehicle with an expected vehicle age of about 150,000 miles in 10 years, the effective battery thermal management system battery energy consumption accounts for about 0.5%-5% of the total energy consumption. However, the effect of this measure on the expected life expectancy will enable the battery to provide 4-6 times the excess energy of this energy consumption. Thermal management has a net positive effect on the cycle life of the battery. Rami Sabbah et al. [29] established a mathematical model of active cooling (air cooling) and a mathematical model of passive cooling (phase change material cooling), and numerically simulated the thermal management system of hybrid electric vehicles. The comparison shows that the passive cooling method of the phase change material can effectively control the temperature of the battery within the safe upper limit, and also has a very good effect in maintaining the temperature uniformity of the battery pack. The air cooling method requires a turbulent air flow rate at high ambient temperature, which will have a great impact on the battery temperature uniformity, and maintaining the battery temperature within the required range also consumes more battery energy. The comparison shows that in terms of temperature control and energy saving effects, phase change cooling has greater advantages than active cooling.
5. Research on Thermal Management Measures for the Whole Life Cycle

The full life cycle of the battery is an important issue in the field of new energy, which refers to the process from the production of battery cells, the whole package assembly to the charging and discharging use, and the maintenance and disposal. Various external factors in the cycle all affect the performance of the battery. From the perspective of the research direction of lithium battery aging, the research on aging mechanism and coupling model is getting deeper and deeper. In the process of building most battery thermal management systems, it is mainly to study the heat balance problem during a certain working condition, and the heat production and power changes of the battery during the whole research process are not the main considerations. Comprehensive considerations about battery aging and thermal management measures are relatively rare. This article mainly explores the control strategies of thermal management from the perspective of the battery life cycle.

5.1. Work at Present

Due to many external factors that affect battery aging, changing ambient temperature, potential physical collisions, complex driving conditions, etc. will make the research on battery aging in the whole life cycle more complicated. Therefore, it is necessary to control the relevant variables and explore the changes in the management and control laws of thermal management measures in the wide time domain of the whole life cycle. For the convenience of follow-up research, it is assumed that the charge and discharge current and cycle of the battery maintain a certain regularity throughout its life cycle. That is, the cyclic aging and calendar aging equivalents are independent variables with respect to time, which facilitates the study of the law of the increase in resistance and heat production with time during the decay process of the battery.

This article uses NCM (LiNi$_{1-x-y}$Co$_x$Mn$_y$O$_2$) lithium-ion batteries produced by Samsung. Based onamesim one-dimensional software, a dynamic semi-empirical aging model is used to simulate the law of battery capacity decay and internal resistance increase during the full life cycle. Based on the change in the heat production law of the battery during the whole life cycle, appropriate direct cooling heat management measures are taken to observe the change law of the battery temperature.

5.1.1. Description of cycle conditions. The cycle conditions describe the driving state of the car within a certain time range. Before exploring the battery cycle aging, it is necessary to give the daily driving situation of the electric car. As shown in Figure 2, it shows the change of the discharge rate of the electric vehicle battery over time each day, and the charge and discharge cycle is performed in the unit of day during the whole life cycle. Driving at a constant speed of 48km/h for half an hour from 7:00 to 7:30 every morning. This section is used as a commuting driving condition for daily use of electric vehicles. The discharge rate is 0.8 C. The acceleration per hundred kilometers of the BMW i3 electric vehicle is 3.86 m/s$^2$, and it can accelerate to 100 km/h in 7.2 s, so the acceleration phase in the cyclic operating condition can be ignored. Similarly, from 5:30 to 6:00 in the afternoon, it was driven at a constant speed of 48km/h for half an hour, as the driving condition for commuting after get off work, and the discharge rate was 0.8 C. From 8:00 to 8:45 in the evening, fast charging is performed at a charging rate of 1 C.
5.1.2. Battery thermal management system adopts feedforward signal. During the battery cycle, the increase in internal resistance and the increase in heat production will make constant thermal management measures unable to meet the battery’s heat dissipation needs. At this time, a feed-forward signal idea can be put forward, that is, the cooling capacity needs to be increased in advance with the passage of battery usage time to cope with the increase in battery heat production. Due to the hysteresis of the system's response to the battery temperature, coupled with the slowness of the heat transfer process itself, the adjustment effect of thermal management measures will be delayed to a certain extent. This is also necessary for feedforward measures. Therefore, some time nodes can be selected in the whole life cycle, and the cooling capacity of the thermal management system can be given an increase in advance according to the increase in battery heat production. Figure 3 shows the control flow of the refrigerant flow over time.

Figure 2. Daily cycle chart.

**Figure 3.** The control flow of refrigerant flow changes with time.
5.1.3. 

Examples of fixed condition. One-dimensional simulation calculation of the battery pack model based on the cycle conditions described above. The results show that when the cycle reaches 10 years, the battery capacity decays to 80% of the field capacity, reaching the scrap standard. In the first 5 years of the cycle, the battery's heat production power did not change significantly. After the cycle exceeded 5 years, the battery's heat production began to increase slowly. Because the heat production of the battery fluctuates in a discharge condition. In order to show the changes in the heat production of the battery in different years, the average value of the battery during the cooling process of 35°C to 30°C is taken to describe the heat production change during the whole life cycle. As shown in Figure 4, the change of heat production with time approximately conforms to the increasing trend of an exponential function.

![Battery heat generation change with time.](image)

Figure 4. Battery heat generation change with time.

Perform a simulation calculation on the NCM lithium-ion battery with a capacity of 94 Ah just after delivery. The battery's initial temperature and room temperature are 30 °C, and the battery runs at a fixed operating condition with a discharge rate of 0.8 C. The inlet flow rate of the cold plate in the direct cooling system is 0.013 kg/s, the inlet temperature is 15 °C, and the inlet pressure is 488kpa. The temperature threshold for starting the direct cooling system is set to 35 °C. When the battery temperature rises to 35 °C, the direct cooling system starts and the battery drops to 30 °C after 864 s. For batteries in different stages of aging, the heat production is greater or lesser than that at the factory. The stage of small heat production will take longer to decrease from the temperature threshold to room temperature. In the later stage of aging, the original flow rate cannot even reduce the battery to room temperature, which increases the risk of thermal runaway. In order to maintain the cooling effect of the refrigeration system throughout its life cycle, it is necessary to set the cooling capacity increment year by year. Taking the battery temperature drop time within 900 s as the optimization target, the corresponding table of the required flow rate of the refrigerant for different stages of aging is obtained. Table 3 and Figure 5 show how the refrigerant flow is adjusted over time.

| Time(year) | 1   | 5   | 6   | 7   | 8   | 8.5 | 9   | 9.25 | 9.5 | 10  |
|-----------|-----|-----|-----|-----|-----|-----|-----|------|-----|-----|
| Refrigerant inlet flow (kg/s) | 0.013 | 0.013 | 0.014 | 0.014 | 0.015 | 0.016 | 0.019 | 0.022 | 0.025 | 0.027 |

Table 3. Refrigerant flow is adjusted over time.
Through this simulation study, it can be found that in the first 5 years, the heat production of the battery changes little, and the original refrigerant flow rate can meet the temperature drop demand. Smaller flow increment required in 5 to 8 years. After 8 years, the refrigerant flow rate will have a similar exponential growth change, which also corresponds to the change trend of the battery internal resistance decay and heat generation in the later stage of aging. Therefore, in the battery life cycle, it is necessary to estimate the heat generation law according to the battery aging degree and adopt the corresponding feedforward strategy. This simulation study is aimed at the battery aging law under constant working conditions and cycles, and external complex factors such as complex working conditions and the influence of external radiation on battery aging will be considered in subsequent studies.

5.2. Work in the Future

(1) In actual driving, electric vehicles often involve complex and changeable working conditions, such as acceleration, climbing, and brake recovery. The driving habits of different drivers are different. All of these will affect the difference in capacity attenuation, resistance increase, and heat generation increase over the full life cycle of the battery. This also puts forward higher requirements for the threshold control of the thermal management system. Thermal management measures under variable load and variable conditions are worth studying in the future.

(2) In the actual driving process, many external factors will cause the aging of the battery to be uncertain. Such as regional factors, time-domain factors, battery factory inconsistency, and differences caused by later management and control. For a thermal management system, these differences can be reasonably summarized on the basis of sufficient experimental data. It is also possible to introduce gain coefficients to normalize different external factors. Finally, a set of thermal management methods and mechanisms for the whole life cycle problem can be proposed.

(3) Regarding the thermal management method and mechanism of the power battery, it can also be introduced into the thermal management of the entire vehicle, and various vehicle components will also have the most profitable temperature range during use. Battery packs require strict temperature management because of their expensive cost. The introduction of thermal management into the vehicle system will inevitably increase energy loss and use costs. This is also a problem worth considering in the future. Figure 6 shows the outlook on the whole life cycle issues.

Figure 5. Refrigerant flow rate adjustment with time.
6. Conclusion

(1) This article first reviews the research on battery aging from three perspectives: aging mechanism, aging model and thermal management measures. On the basis of summarizing the internal mechanism of battery aging, the coupling relationship with the thermoelectric model and its application status are analyzed. Finally, the current general thermal management methods are explained, and the positive significance of effective thermal management measures in delaying battery aging and improving battery energy utilization is clarified.

(2) Conducted a preliminary study on the tracking control of battery thermal management throughout the life cycle. On the basis of simulating and studying the increase of battery internal resistance and the change of heat generation during the whole life cycle, the heat management control idea of feedforward signal is proposed. With changing refrigerant flow, the consistency of the temperature drop effect of the direct cooling system is maintained in the time dimension of the whole life cycle.

(3) Thermal management research that considers aging should continue to expand to the research background of variable operating conditions and all factors. In addition to formulating a set of methods to manage the aging of the battery system for the entire life cycle of the battery system, thermal management measures for other components are also issues worthy of study. This will play an important role in the maintenance of vehicle-level performance and the improvement of durability.

Acknowledgments
Authors wishing to acknowledge assistance or encouragement from my tutor Gao Qing and my teacher Wang Guohua.

References
[1] Agubra V, Fergus J. Lithium Ion Battery Anode Aging Mechanisms [J]. Materials (Basel), 2013, 6(4): 1310-1325.
[2] Yunjian Li, Kuining Li, Yi Xie, Jiayuan Liu, Chunyun Fu, Bin Liu, Optimized charging of lithium-ion battery for electric vehicles: Adaptive multistage constant current–constant voltage charging strategy, Renewable Energy, Volume 146, 2020, Pages 2688-2699.
[3] Rui Zhao, Junjie Gu, Jie Liu. An experimental study of heat pipe thermal management system with wet cooling method for lithium ion batteries[J]. Journal of Power Sources. 2015:273:1089-1097
[4] Vetter J, Novák P, Wagner M R, et al. Ageing mechanisms in lithium-ion batteries[J]. Journal of Power Sources, 2005, 147(1-2): 269-281.
[5] Bin Pan, Dong Dong, Jionggeng Wang, Jianbo Nie, Shuangyu Liu, Yaohe Cao, Yinzhu Jiang, Aging mechanism diagnosis of lithium ion battery by open circuit voltage analysis, Electrochimica Acta, Volume 362, 2020, 137101, ISSN 0013-4686,

[6] Broussely M, Biensan P, Bonhomme F, et al. Main aging mechanisms in Li ion batteries[J]. Journal of Power Sources, 2005, 146(1-2): 90-96.

[7] Y. Wang, X. Guo, S. Greenbaum, J. Liu, K. Amine. Solid electrolyte interphase formation on lithium-ion electrodes: a 7Li nuclear magnetic resonance study. Electrochem Solid State Lett, 4(2002), pp.A68-A70.

[8] Koltypin M, S.Cohen Y, Markovsky B, et al. The study of lithium insertion–deinsertion processes into composite graphite electrodes by in situ atomic force microscopy (AFM)[J]. Electrochemistry Communications, 2002, 4(1): 17-23.

[9] Han X, Ouyang M, Lu L, et al. A comparative study of commercial lithium ion battery cycle life in electrical vehicle: Aging mechanism identification[J]. Journal of Power Sources, 2014, 251: 38-54.

[10] Marc Doyle, Thomas F. Fuller, John Newman. Modeling of Galvanostatic Charge and Discharge of the Lithium/Polymer/Insertion Cell. 2019, 140(6)

[11] T.R. Ashwin, A. McGordon, W.D. Widanage, P.A. Jennings, Modified electrochemical parameter estimation of NCR18650BD battery using implicit finite volume method, Journal of Power Sources, Volume 341, 2017, Pages 387-395, ISSN 0378-7753,

[12] Ramadass, P., Haran, B., Gomadam, P.M., White, R., Popov, B.N. Development of First Principles Capacity Fade Model for Li-Ion Cells(2004) Journal of the Electrochemical Society, 151(2), pp. A196-A203.

[13] C. Edouard, M. Petit, C. Forgez, J. Bernard, R. Revel, Parameter sensitivity analysis of a simplified electrochemical and thermal model for Li-ion batteries aging, Journal of Power Sources, Volume 325, 2016, Pages 482-494, ISSN 0378-7753,

[14] Safarî, M., Morcrette, M., Teyssot, A., Delacourt, C. Multimodal physics-based aging model for life prediction of Li-Ion batteries(2009) Journal of the Electrochemical Society, 156(3), pp. A145-A153.

[15] Shriram Santhanagopalan, Qingzhi Guo, Premanand Ramadass, Ralph E. White, Review of models for predicting the cycling performance of lithium ion batteries, Journal of Power Sources, Volume 156, Issue 2, 2006, Pages 620-628, ISSN 0378-7753.

[16] P. Ramadass, Bala Haran, Ralph White, Branko N. Popov, Mathematical modeling of the capacity fade of Li-ion cells, Journal of Power Sources, Volume 123, Issue 2, 2003, Pages 230-240, ISSN 0378-7753.

[17] John Wang, Ping Liu, Jocelyn Hicks-Garner, Cycle-life model for graphite-LiFePO4 cells, Journal of Power Sources 196 (2011) 3942–3948, HRL Laboratories, LLC, Malibu, CA 90265, United States

[18] I Bloom, B.W Cole, J.J Sohn, E.G Polzin, V.S Battaglia, G.L Henriksen, C Motloch, R Richardson, T Unkelhaeuser, D Ingersoll, H.L Case, An accelerated calendar and cycle life study of Li-ion cells, Journal of Power Sources, Volume 101, Issue 2, 2001, Pages 238-247, ISSN 0378-7753.

[19] Madeleine Ecker and others. Development of a lifetime prediction model for lithium-ion batteries based on extended accelerated aging test data [J], Journal of Power Sources, 2012(215): 248–257.

[20] Johannes Schmalstieg, Stefan Käbitz, Madeleine Ecker, Dirk Uwe Sauer, A holistic aging model for Li(NiMnCo)O2 based 18650 lithium-ion batteries, Journal of Power Sources 257 (2014) 325e334, Aachen University.

[21] Guiwen Jiang, Ling Zhuang, Qinghua Hu, Ziqiang Liu, Juhua Huang, An investigation of heat transfer and capacity fade in a prismatic Li-ion battery based on an electrochemical-thermal coupling model, Applied Thermal Engineering, Volume 171, 2020, 115080, ISSN 1359-4311.

[22] Jaeshin Yi, Boram Koo, Chee Burm Shin, Taeyoung Han, Seongyong Park, Modeling the effect of aging on the electrical and thermal behaviors of a lithium-ion battery during constant current
charge and discharge cycling, Computers & Chemical Engineering, Volume 99, 2017, Pages 31-39, ISSN 0098-1354.

[23] Thomas Waldmann, Marcel Wilka, Michael Kasper, Meike Fleischhammer, Margret Wohlfahrt-Mehrens, Temperature dependent ageing mechanisms in Lithium-ion batteries – A Post-Mortem study, Journal of Power Sources, Volume 262, 2014, Pages 129-135, ISSN 0378-7753.

[24] Rajib Mahamud, Chanwoo Park. Reciprocating air flow for Li-ion battery thermal management to improve temperature uniformity. 2011, 196(13):5685-5696.

[25] Haitao Wang, Tao Tao, Jun Xu, Xuesong Mei, Xiaoyan Liu, Piao Gou, Cooling capacity of a novel modular liquid-cooled battery thermal management system for cylindrical lithium ion batteries, Applied Thermal Engineering, Volume 178, 2020, 115591, ISSN 1359-4311

[25] Joshua Smith, Michael Hinterberger, Peter Hable, et al. Simulative method for determining the optimal operating conditions for a cooling plate for lithium-ion battery cell modules. 2014, 267:784-792.

[26] Yan-Feng Wang, Jiang-Tao Wu, Thermal performance predictions for an HFE-7000 direct flow boiling cooled battery thermal management system for electric vehicles, Energy Conversion and Management, Volume 207, 2020, 112569, ISSN 0196-8904,

[28] Gros Oliver & Clark Steven. (2011). Optimizing Electric Vehicle Battery Life through Battery Thermal Management. SAE International Journal of Engines. 4. 1928-1943. 10.4271/2011-01-1370.

[29] Rami Sabbah, R. Kizilel, J.R. Selman, S. Al-Hallaj, Active (air-cooled) vs. passive (phase change material) thermal management of high power lithium-ion packs: Limitation of temperature rise and uniformity of temperature distribution, Journal of Power Sources, Volume 182, Issue 2, 2008, Pages 630-638, ISSN 0378-7753.