MODELLING AND ANALYSIS

An optimization model based on temperature field and series–parallel structure for battery-package of a stratospheric airship

Yan Wang\textsuperscript{1,2} | Zhaojie Li\textsuperscript{1,2} | Yanlei Zhang\textsuperscript{1,2} | Xuwei Wang\textsuperscript{1} | Yang Gao\textsuperscript{1,2}

\textsuperscript{1}Department 10, Aerospace Information Research Institute, Chinese Academy of Sciences, Beijing, China
\textsuperscript{2}School of Electronic, Electrical and Communication Engineering, University of Chinese Academy of Sciences, Beijing, China

Correspondence
Yanlei Zhang, Department 10, Aerospace Information Research Institute, Chinese Academy of Sciences, No. 9 Dengzhuang South Road, Beijing 100094, China.
Email: zhangyanlei@aoe.ac.cn

Funding information
National Natural Science Foundation of China, Grant/Award Numbers: 51606197, 51707189

Abstract
Stratospheric airships are long-endurance flight platforms that utilize renewable energy systems. The solar array in these systems cannot generate electricity at night; only an energy storage battery pack can be used to power the entire system. Therefore, accurate modeling and estimation of the output characteristics and operating conditions of battery packs have become the focus of current research. During the actual flight of an airship, uneven temperature distribution causes changes in the output characteristics and differences in the cell voltage of the battery packs. To address this problem, this study establishes an output characteristic model, series–parallel structure coupled with a temperature field model (SPTM), for a battery pack based on the series–parallel structure of a single cell. In addition, the influence of temperature distribution was considered in the model. Then, a flight verification test was conducted, and the test data and simulation data were compared. The average absolute error of the SPTM was maintained at approximately 0.61 V, which accurately reflected the output characteristics of the battery pack. The simulation model was then used to study the cell voltage difference under changes in the temperature distribution and demonstrate the relationship between the cell voltage difference and temperature difference.

KEYWORDS
battery package, stratospheric airship, temperature field, voltage difference

1 | INTRODUCTION

Stratospheric airships\textsuperscript{1,2} as long-endurance, heavy-load flight platforms, have high scientific and military value for all countries, as shown in Figure 1. Because of the long-endurance flight requirements, stratospheric airships use renewable energy systems\textsuperscript{3} to ensure energy supply, as shown in Figure 2. For the flight during daytime, the solar array not only powers the equipment but also charges the energy storage battery pack. When flying at night, there is no solar input, and only the energy storage battery pack powers the airship. Because of the limitations of weight and energy density, the energy storage battery pack cannot provide the same output power at night as during the day\textsuperscript{4,5} and the working temperature and charge/discharge rate affect the...
available capacity of the battery pack. Therefore, current studies focus on maintaining the working state of the energy storage battery pack, calculating the available capacity under different environmental impacts.

In the past decades, researchers have focused on the energy management system and energy balance of stratospheric airships. Sun et al. extensively analyzed the structure of the high-safety energy storage system of a stratospheric airship and studied the energy management system of the airship. Then, the energy management software was verified through charge and discharge tests. They proposed the use of the Ah integral method to estimate the SOC of energy storage batteries to achieve higher estimation accuracy. Zhang et al. proposed using different flight strategies to solve the limited capacity of the energy storage battery of an airship. This can effectively improve the endurance ability of these airships. In this study, the power integral method was used to calculate the SOC and analyze the airship’s endurance ability. Xiaowei et al. proposed a method for determining the remaining life based on the internal resistance of the energy storage battery pack. The author verified through experiments that internal resistance is a function of the remaining life, and an accurate remaining life can be determined through this relationship. However, these studies were only conducted from the perspective of energy balance, ignoring the influence of the operating temperature on the available capacity. Compared to a suitable operating temperature, a lower operating temperature would decrease the available capacity of the energy storage battery pack. Therefore, it is very important to establish an optimization model that considers the temperature distribution of the energy storage battery pack.

Zhou et al. studied the heat convection and transfer of energy storage battery packs under high-rate discharge to analyze the thermal characteristics and output power performance analysis of the battery packs. Modeling simulation and experimental verification revealed that the battery

**FIGURE 1** Structure of the stratospheric airship

**FIGURE 2** The power train of the stratospheric airship
pack is often in a situation where its internal temperature is uneven during operation. The working temperature distribution is also related to the battery discharge depth. Zhang et al.\textsuperscript{13} studied a battery pack under air-cooled heat transfer conditions. They analyzed the electrical performance of the battery pack and found that its working temperature is closely related to the discharge rate and heat transfer environment. They verified through experiments that the available capacity decreases as the temperature decreases in a low-temperature environment. Therefore, this study introduced the operating temperature into the energy storage battery pack model to more accurately reflect the operating status and available capacity.

The energy storage battery pack for stratospheric airships is composed of single cells combined in an m-series n-parallel connection. The cells are connected using conductive nickel belts. Owing to the weight limitation of the energy system, an energy storage battery pack cannot be installed with a battery cell temperature control system. Thus, it is impossible to ensure that each battery cell operates at the same temperature during flight. The difference in operating temperature affects the internal resistance of the battery pack, and thus affects its usable capacity.\textsuperscript{14–16}

Ko et al.\textsuperscript{17} proposed a battery pack modeling method with equivalent series as well as parallel resistance and capacitance. In this method, the ohmic internal resistance, polarization internal resistance, and polarization capacitance of the lithium battery are connected in series and parallel to form a lumped resistance for calculation. This method can reflect the different initial internal resistances of the battery cells. The internal resistance of the cells cannot be updated in real time with the change in the working state of the battery. Moreover, for a multi-series–parallel battery pack, this method cannot accurately reflect the internal resistance of the battery caused by the uneven temperature distribution. In the above-mentioned studies, the entire battery pack is considered as a single unit to establish a lumped model. The working characteristics of the single cells in the battery pack are ignored, hindering the model from accurately reflecting the working state of the battery cells under different temperature distributions. Bruen and Mraco\textsuperscript{18} connected single cells in parallel to form a group and calculated their current distribution and dynamic characteristics during operation. Experiments verified that the modified model can accurately reflect the working state of a single cell in the parallel state. In summary, this article proposes an optimization model (series–parallel structure coupled with a temperature field model [SPTM]) for an energy storage battery pack that considers the operating temperature of every single cell and the series–parallel structure. The SPTM can accurately reflect the changes in the battery state caused by changes in the temperature distribution in the battery pack.

2 | MODEL DEVELOPMENT

In this section, an output characteristic model (SPTM) for a battery pack based on the series–parallel structure of a single cell is established. The terminal voltage and output power of the battery pack were calculated. This modeling method cannot only accurately reflect the temperature distribution in the battery pack, but also estimate the single-cell voltage difference during the operating process.

2.1 | ECM of a single cell

Commonly used lithium battery models include electrochemical, electrothermal, and Equivalent Circuit Model (ECM).\textsuperscript{19} Although electrochemical and electrothermal models can accurately describe the internal chemical reactions of lithium batteries, their complicated input and large calculations make them unsuitable. The ECM is commonly used to simulate the voltage response of individual cells because of its relative simplicity, ease of parameterization, and real-time feasibility.\textsuperscript{20,21} For the energy storage system design and energy balance analysis, this study adopted the second-order RC equivalent circuit method to model a single cell. The equivalent circuit model is illustrated in Figure 3.

In this model, $U_{\text{ocv}}$ represents the open-circuit voltage of a single cell, and $U_L$ represents the terminal voltage of a single cell. According to Kirchhoff’s voltage law and the full response principle of the second-order circuit, the voltage relationship of the equivalent circuit model can be expressed as

$$U_L = U_{\text{ocv}} - U_{\text{ohm}} - U_{p1} - U_{p2},$$

where $U_{\text{ocv}}$ and the State Of Charge (SOC) of the single cell have a nonlinear corresponding relationship, which was measured experimentally. Therefore, the $U_{\text{ocv}}$ of the battery can be obtained from the SOC as follows:

$$U_{\text{ocv}} = f(SOC(t)),$$

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure3}
\caption{ECM of the single cell}
\end{figure}
where \( SOC(t) \) is the SOC at time \( t \) and can be expressed as

\[
SOC(t) = SOC(t_0) + \frac{1}{C} \int_{t_0}^{t} \eta_i \cdot I_{cell}(t) \, dt,
\]

(3)

where \( SOC(t_0) \) represents the initial SOC of the single cell, \( C \) represents the rated capacity of the battery, \( \eta_i \) represents the Coulomb efficiency, and \( I_{cell}(t) \) represents the current value at time \( t \).

\( U_{ohm} \) represents the voltage of the ohmic internal resistance, and \( U_{p1} \) and \( U_{p2} \) represent the voltages of the polarization internal resistance, which can be calculated as

\[
\begin{align*}
U_{ohm} &= R_{ohm} \cdot I_{cell}, \\
U_{p1} &= I_{cell} \cdot R_{p1} \cdot e^{-\frac{U_{p1}}{C}}, \\
U_{p2} &= I_{cell} \cdot R_{p2} \cdot e^{-\frac{U_{p2}}{C}},
\end{align*}
\]

(4)

where \( R_{ohm} \) represents the ohmic internal resistance, \( R_{p1} \) and \( R_{p2} \) represent the polarization internal resistances, \( C_{p1} \) and \( C_{p2} \) represent the polarization capacitances, \( I_{cell} \) represents the load current of the single cell, and \( T_c \) represents the sampling time. In addition, the internal resistance and polarization capacitance are functions of the SOC and operating temperature; therefore, the internal resistance and polarization capacitance are calculated as follows:

\[
\begin{align*}
R_{ohm} &= f(SOC_{cell}, T_{cell}), \\
R_{p1} &= f(SOC_{cell}, T_{cell}), \\
R_{p2} &= f(SOC_{cell}, T_{cell}), \\
C_{p1} &= f(SOC_{cell}, T_{cell}), \\
C_{p2} &= f(SOC_{cell}, T_{cell}).
\end{align*}
\]

(5)

Finally, we discretized Equations (1), (3), and (4) to obtain the state-space equation. The state-space equation can be expressed as

\[
\begin{bmatrix}
U_{p1,t} \\
U_{p2,t} \\
SOC_{cell,t}
\end{bmatrix}
= 
\begin{bmatrix}
e^{-\frac{U_{p1}}{C}} & 0 & 0 \\
0 & e^{-\frac{U_{p2}}{C}} & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
U_{p1,t-1} \\
U_{p2,t-1} \\
SOC_{cell,t-1}
\end{bmatrix}
+ 
\begin{bmatrix}
R_{p1} \left(1 - e^{-\frac{U_{p1}}{C}}\right) \\
R_{p2} \left(1 - e^{-\frac{U_{p2}}{C}}\right)
\end{bmatrix}
\cdot I_{cell,t-1},
\]

(6)

\[
U_{L,t} = U_{dcv,t} + \begin{bmatrix} 1 & 1 & 0 \end{bmatrix}
\begin{bmatrix}
U_{p1,t} \\
U_{p2,t} \\
SOC_{cell,t}
\end{bmatrix}
+ R_{ohm} \cdot I_{cell,t}.
\]

2.2 Series–parallel model of a battery pack

The energy storage battery pack is composed of single cells combined with \( m \) series and \( n \) parallels. The equivalent circuit model is illustrated in Figure 4. Each series branch is composed of \( n \) single cells in parallel and the parallel net structure of the battery pack is shown in Figure 5. According to Kirchhoff’s current law, the current relationship of the parallel net can be expressed as

\[
I_{cell,n-1} = I_n - I_{n-1},
\]

\[
I_{cell,n} = I_{n+1} - I_n.
\]

(7)

According to Kirchhoff’s voltage law, the voltage relationship of the parallel net can be expressed as
**FIGURE 5** Parallel net structure of the battery package

\[ U_{ocv,n} + U_{p,n} - U_{ocv,n-1} - U_{p,n-1} + I_{cell,n} \cdot R_{ohm,n} \]

\[ - I_{cell,n-1} \cdot R_{ohm,n-1} + 2 \cdot I_n \cdot R_c = 0, \]

\[ U_{p,n} = U_{p1,n} + U_{p2,n}, \]

\[ U_{p,n-1} = U_{p1,n-1} + U_{p2,n-1}, \]

where \( R_c \) is the resistance of the nickel band. Therefore, \( I_{cell} \) can be calculated by combining Equations (7) and (8) as follows:

\[
\begin{pmatrix}
I_{cell,1} \\
I_{cell,2} \\
\vdots \\
I_{cell,n}
\end{pmatrix} = G \times R^{-1} \times (E \times U + F \cdot I_h),
\]

\[
G = \begin{pmatrix}
1 & -1 & 0 & 0 \\
0 & 1 & -1 & 0 \\
0 & \ddots & 1 & -1 \\
0 & \cdots & 0 & 1
\end{pmatrix},
\]

\[
E = \begin{pmatrix}
0 & 0 & \cdots & 0 \\
-1 & 1 & 1 & 0 & \cdots & 0 \\
0 & \cdots & -1 & 1 & 1 & 0 & 0 \\
0 & \cdots & 0 & -1 & -1 & 1 & 1
\end{pmatrix},
\]

\[
F = \begin{pmatrix}
1 \\
0 \\
\vdots \\
0
\end{pmatrix}
\]

\[
U_{ocv} + U_{p1} + U_{p2} = \text{max}(U_{ocv}) + U_{p1} + U_{p2}.
\]

\[
U_{ocv,n} + U_{p1,n} + U_{p2,n} = \text{max}(U_{ocv,n}) + U_{p1,n} + U_{p2,n}.
\]

Therefore, the battery terminal voltage \( U_{L,n} \) in the parallel network can be calculated using the current \( I_{cell,n} \) as follows:

\[
U_{L,n} = U_{ocv,n} + R_{ohm,n} \cdot I_{cell,n} + I_{cell,n} \cdot R_{p1,n} \\
\cdot e^{-\frac{R_{pr1,n}}{R_{ohm,n}}} + I_{cell,n} \cdot R_{p2,n} \cdot e^{-\frac{R_{pr2,n}}{R_{ohm,n}}}.
\]

In summary, the total voltage of the energy storage battery pack can be calculated by adding the voltages of the branches in series as follows:

\[
U_{L,h} = \sum_{i=1}^{m} \text{max}(U_{L,x}).
\]

## 3 | EXPERIMENTAL PROCEDURE

For the models of the single cell and series-parallel structure proposed in Sections 2.1 and 2.2, parameter identification experiments are performed to determine the various
parameters. Simultaneously, the characteristic parameters are affected by the operating temperature of the single cell. Thus, it is essential to determine the internal temperature of a battery pack. The working temperature of each single can be obtained from the temperature field fitted by the measurement data. Then, the working temperature is used as the model input to calculate the SOC of the energy storage battery pack under the influence of temperature fields. Finally, the SPTM was verified and the model error was calculated by comparing the discharge data of the energy storage battery pack in the verification flight test with the simulated data.

3.1 Parameter identification experiment

The experimental parameters determined for the single-cell model are presented in Table 1. To obtain accurate parameters, the constant current intermittent discharge (CCID) test method was used for the experiment, and the experimental data are shown in Figure 6. In the experiment, the discharge time was 360 s and the standing time was 1800 s. The terminal voltage after standing is approximately the \( U_{ocv} \) value of a single cell. Therefore, the nonlinear functional relationship between the \( U_{ocv} \) and the SOC can be obtained through the test, as shown in Figure 7. At the moment of discharge, \( R_{ohm} \) can be obtained by reducing the battery voltage and the discharge current. The nonlinear functional relationship between the \( R_{ohm} \) and the SOC is shown in Figure 8. The functional relationship between \( R_{p1}, R_{p2}, C_{p1}, C_{p2} \), and SOC can be obtained through the voltage rebound process at the end of discharge.

In contrast to the traditional model, after obtaining the characteristic parameters of the battery cells, SPTM calculates the working characteristics of each battery cell and then considers the series-parallel structure of the battery cells to determine the overall working characteristics of the energy storage battery pack. This method can accurately reflect the impact of the changes in each cell in the battery pack during operation. Each battery cell is refined by calculating its operating characteristics at different temperatures to more accurately reflect the operating characteristics of the energy storage battery pack.

3.2 Flight verification experiment

The energy storage battery pack used in this flight test is composed of 3510 single cells, 45 in parallel and 78 in series. These single cells were divided into six battery

| TABLE 1 | Some parameter of single cell |
|----------|------------------------------|
| **Parameter** | **Value** |
| Category | Li (NiCoMn) O₂ |
| \(U_{ocv} (V/\text{SOC:100\%})\) | 4.196 |
| \(U_{ocv} (V/\text{SOC:0\%})\) | 3.225 |
| Discharge capacity (Ah) | 3.2 |
| Environment temperature (°C) | 25°C |
| Discharge current (A) | 1.6/0.5 C |
| Time of intermittent charge (s) | 360 |
| Time of intermittent quality (s) | 1800 |
modules, each consisting of 585 single cells that are divided into 13 branches in series. Each module was assembled as a double-layered structure and protected by an aluminum shell. In the energy storage battery module, to use the least temperature points to reflect the most comprehensive temperature information, after careful consideration, ten temperature probe points were arranged in each energy storage battery pack, which were arranged in two layers. There were five temperature probes on each layer. The location of the temperature probes and the internal structure of the battery pack are shown in Figure 9. The parameters of the energy storage battery pack evaluated through the flight test are listed in Table 2.

The six battery modules were installed at different positions in the airship pod. Owing to the difference in the heat transfer conditions of each module, the operating temperatures of the battery modules are different. Furthermore, owing to the difference in the distance between the single cells and the shell inside the battery module, temperature differences also occurred between the single cells. During the flight test, the internal temperature field of the battery module was fitted by analyzing the temperature data at different measurement points. Then, the temperature difference was calculated through the temperature field. The highest and lowest cell temperatures are shown in Figure 10. The internal temperature differences are shown in Figure 11.

In the flight test, the airship flies during the day and at night. It operates in a charged state during the day, and the energy storage battery operates in a discharged state at night. The charging and discharging currents of the energy storage battery pack during the flight are shown in Figure 12.

The model was verified according to the above test conditions. As shown in Figure 13, The highest absolute error (AE) of SPTM was 3.508 V, and the highest relative error (RE) was 1.21%, and the average absolute error was 0.61 V, which verified the correctness of SPTM.

4 | RESULTS AND DISCUSSION

4.1 | Simulation results and error analysis

This simulation experiment used two different modeling methods to calculate the SPTM and second-order RC models. Then, the simulation results of the two methods were compared and analyzed. The terminal voltage change and the highest cell voltage difference of the energy storage battery pack during operation were
obtained after introducing the flight test parameters into the simulation program. The simulation results are presented in Figure 13.

The second-order RC model used the average temperature as the input variable for the terminal voltage of the energy storage battery pack. The average temperature cannot accurately reflect the internal temperature distribution of the battery pack and ignores the working state of a single cell. Therefore, in the simulation process, the error increased as the internal temperature difference of the battery pack increased, and the error was highest during high-rate discharge. The simulation error of the second-order RC model, which was larger than the error of the SPTM (0.5 V), reached 2 V at the same discharge capacity at the end of discharge. Simultaneously, the temperature difference in the battery pack increased owing to the self-heating of the battery during the charging process, and the error of the second-order RC model further increased.
The SPTM was used for the simulation because the input variable was the temperature distribution in the battery pack. It could accurately reflect the operating temperature of every single cell. The simulation error did not increase with the increase in temperature difference, but converged within a small error range. Thus, the SPTM could reflect the working state of the energy storage battery pack under a change in temperature distribution with high simulation accuracy.

The highest AE of SPTM was 3.508 V, and the highest RE was 1.21%. The highest AE of the second-order RC model was 6.099 V, while the highest RE was 2.123%. A comparison of the two models showed that the highest AE of SPTM was reduced by 42.48%, and the RE was reduced by 43.01%. A comparison of the AEs of the two simulation models is shown in Figure 14. The error characteristic values are presented in Table 3.

The SPTM not only accurately reflected the terminal voltage of the energy storage battery pack, but also predicted the voltage of the internal single cell. The voltage map of the single cell is shown in Figure 15. The initial voltage difference of the single cell is 0.019 V. The largest voltage difference of the single cell in the battery pack was obtained by calculation, as shown in Figure 16.

Compared with the flight test data, the highest AE of the cell voltage difference obtained by the SPTM simulation was 0.015 V, as shown in Figure 17.

### 4.2 Influence of temperature on the voltage difference of a single cell

During the flight, the cell voltage difference affects the health of the energy storage battery pack. A cell voltage difference of up to 60 mV causes the cell discharge to become unbalanced, and the available capacity decreases after multiple cycles of use. There are further problems so that the cell cannot be charged and discharged. Thus, the use of limited means to control the cell voltage difference has become the focus of recent studies.

An analysis of the flight test data and the simulation data revealed that uneven temperature distribution is an important factor influencing the increase in the cell voltage difference. Therefore, this study reduced the temperature difference of the battery pack for simulation calculation and calculated the cell voltage when the maximum temperature difference was 0°C, 5°C, 10°C, 15°C, and 20°C. The calculation results are shown in Figure 18. From the calculation results, it was found that the highest temperature difference was positively correlated with the difference in cell voltage. When the temperature difference was 0°C, the cell voltage difference fluctuated around the initial voltage difference; when it was 5°C, the cell voltage difference was 0.035 V; and when it was 20°C, the cell voltage difference was approximately 0.11. Furthermore, when the highest
temperature difference increased, the cell voltage difference also increased. Therefore, the highest temperature difference considered in the study should be minimized during the thermal design of an energy storage system. The cell voltage difference was maintained within the normal range.

5 | CONCLUSION

This study analyzed existing battery pack modeling methods, revealing that these modeling methods cannot accurately reflect the output characteristics of energy storage battery packs under the influence of temperature fields. Therefore, this study investigated the single-cell series-parallel structure and the internal temperature distribution law of the battery pack. A model (SPTM) was
proposed for the energy storage battery pack of a stratospheric airship based on a battery cell series-parallel structure coupled with a temperature field to solve the shortcomings of existing modeling methods. Finally, the accuracy of the modeling method was verified using a flight test. The important conclusions of this study are as follows.

(1) The model established for an energy storage battery pack with a series-parallel structure coupled with a temperature field could accurately reflect the operating status of the energy storage battery pack during flight, such as the operating voltage, operating temperature, and highest cell voltage difference. By comparing the flight test data and the simulation data, and the highest AE values of the second-order model obtained by two different methods, the calculation error of the SPTM was reduced by 42.48%, and the RE by 43.01%.

(2) The law of the highest cell voltage difference in the operation of the energy storage battery pack was revealed through the SPTM simulation, with the highest calculation error of 0.015 V. At the design stage, the working state of the energy storage battery pack was simulated and analyzed using the SPTM. According to the simulation calculation results, the thermal design can be optimized, and the difference between the operating temperature and cell voltage difference can be reduced.

(3) By analyzing the SPTM simulation, the highest cell voltage difference can be reduced by reducing the temperature difference during the operation. The calculation showed that when the highest temperature difference was 0°C, the highest cell voltage difference was maintained near the initial voltage difference. When the highest temperature difference increased, the cell voltage difference increased accordingly. Therefore, the highest temperature difference of the energy storage battery pack was minimized in the thermal design stage.

ACKNOWLEDGMENTS
This study is financially supported by the NSFC Grant (Nos. 51707189, 51606197) and the Aerospace Information Research Institute, Chinese Academy of Science.

ORCID
Yan Wang http://orcid.org/0000-0001-8979-924X

REFERENCES
1. Ming Z, Shi Y, Haoquan L, Xiayang Z. Near space airship conceptual design and optimization. J Commun Inform Netw. 2016;1(1):125-133. doi:10.11959/j.issn.2096-1081.2016.011
2. Ozoroski T, Mas K, Hahn A. A PC-based design and analysis system for lighter-than-air unmanned vehicles. 2nd AIAA “Unmanned Unlimited” Conf. and Workshop & Exhibit. 2003: 6566. doi:10.2514/6.2003-6566
3. Liao J, Jiang Y, Li J, et al. An improved energy management strategy of hybrid photovoltaic/battery/fuel cell system for stratospheric airship. Acta Astronaut. 2018;152:727-739. doi:10.1016/j.actaastro.2018.09.007
4. Yu D, Lv X. Configurations analysis for high-altitude/long-endurance airships. Aircr Eng Aerosp Technol. 2010;80:1464-1472. doi:10.1016/j.aerosp.2010.08.020
5. Zhao B, Hu M, Ao X, Huang X, Ren X, Pei G. Conventional photovoltaic panel for nodal radiative cooling and preliminary performance analysis. Energy. 2019;175:677-686. doi:10.1016/j.energy.2019.03.106
6. Sun K, Dong J, He S, et al. Research on management software design of energy storage system for stratospheric airship. Proc Comput Sci. 2017;107:401-407. doi:10.1016/j.procs.2017.03.125
7. Zhang L, Li J, Jiang Y, Du H, Zhu W, Lv M. Stratospheric airship endurance strategy analysis based on energy optimization. Aerospace Sci Technol. 2020;100:105794. doi:10.1016/j.ast.2020.105794
8. Xiaowei D, Guoning X, Zhaojie L, Ying M, Shuai Z, Hao D. Remaining useful life prediction of lithium-ion batteries of stratospheric airship by model-based method. Microelectron Reliab. 2019;100:113400. doi:10.1016/j.microrel.2019.113400
9. Peng X, Chen S, Garg A, Bao N, Panda B. A review of the estimation and heating methods for lithium-ion batteries pack at the cold environment. Energy Syst Eng. 2019;7(3):645-662. doi:10.1016/j.ees3.279
10. Jilte RD, Kumar R, Ma L. Thermal performance of a novel confined flow Li-ion battery module. Appl Therm Eng. 2019;146:1-11.
11. Malik M, et al. Thermal and electrical performance evaluations of series connected Li-ion batteries in a pack with liquid cooling. Appl Therm Eng. 2018;129. doi:10.1016/j.applthermaleng.2017.10.029
12. Zhou S, Song Z, Zhao Y. Analysis of the thermal effect of a lithium iron phosphate battery cell and module. Energy Sci Eng. 2021;9(5):661-675. doi:10.1016/j.eses.851
13. Zhang L, Chen Q, Wang T. Effects of air cooling structure on cooling performance enhancement of prismatic lithium-ion battery packs based on coupled electrochemical-thermal model. Energy Sci Eng. 2021;9:1450-1464. doi:10.1016/j.ees9.905
14. Remmlinger J, Buchholz M, Meiler M, Bernreuter P, Dietmayer K. State resistance matching for parallel connected lithium-ion cells and batteries in electric vehicles by on-board internal resistance estimation. J Power Sources. 2011;196(12):5357-5363. doi:10.1016/j.jpowsour.2010.08.035
15. Zhang Z, Huang X, Jiang J, Wu B. An improved dynamic model considering effects of temperature and equivalent internal resistance for PEM fuel cell power modules. J Power Sources. 2006;161(2):1062-1068. doi:10.1016/j.jpowsour.2006.05.030
16. Gogaona R, Pinson MB, Bazant MZ, Sarma SE. Internal resistance matching for parallel-connected lithium-ion cells and impacts on battery pack cycle life. J Power Sources. 2014;252:8-13. doi:10.1016/j.jpowsour.2013.11.101
17. Ko ST, Lee J, Ahn JH, Lee BK. Innovative modeling approach for Li-ion battery packs considering intrinsic cell unbalances and packaging elements. Energies. 2019;12(3):356. doi:10.3390/en12030356
18. Bruen T, Marco J. Modelling and experimental evaluation of parallel connected lithium ion cells for an electric vehicle battery system. *J Power Sources*. 2016;310:91-101. doi:10.1016/j.jpowsour.2016.01.001

19. Liang C, Li Y, Luo J. Battery modeling methods for electric vehicles—a review. 2014 European Control Conference (ECC). IEEE. 2014:2673-2678. doi:10.1109/ECC.2014.6862541

20. Hu X, Li S, Peng H. A comparative study of equivalent circuit models for Li-ion batteries. *J Power Sources*. 2012;198:359-367. doi:10.1016/j.jpowsour.2011.10.013

21. Seaman A, Dao TS, McPhee J. A survey of mathematics-based equivalent-circuit and electrochemical battery models for hybrid and electric vehicle simulation. *J Power Sources*. 2014;256:410-423. doi:10.1016/j.jpowsour.2014.01.057

22. Feng X, Gooi HB, Chen SX. An improved lithium-ion battery model with temperature prediction considering entropy. 2012 3rd IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe). IEEE. 2012;1-8. doi:10.1109/ISGTEurope.2012.6465668

How to cite this article: Wang Y, Li Z, Zhang Y, Wang X, Gao Y. An optimization model based on temperature field and series-parallel structure for battery-package of a stratospheric airship. *Energy Sci Eng.* 2022;10:1986-1997. doi:10.1002/ese3.1113