Fault Tolerance Optimization of a Lithium Battery Pack Having a Damaged Unit

Fusheng Gu, Zhenmu Chen, Ming Wang, and Zhenzhe Li*

ABSTRACT: As a kind of green and sustainable technology, electric vehicles are continuously highlighted for solving the significant problems of energy and air pollution. In this paper, fault tolerance optimization of an air-cooled lithium battery pack having a damaged unit was considered to improve the heat dissipation performance. For constructing the relationship between the objective function and the design variables, a quadratic polynomial response function was set up based on the experimental points, which were selected by the Latin-hypercube design of experiment method. Then, a multi-island genetic algorithm-based optimization of the battery pack having a damaged unit was performed under the condition of adjusting the flow velocity of each inlet. The results show that the acceptable temperature differences were obtained under the condition of fixing the total mass flow rate of the inlets. The simulation and fault tolerance optimization methods recommended in this study can be widely used to improve the real safety level of the systems.

1. INTRODUCTION

In recent years, traditional fuel vehicles have been increasingly replaced by electric vehicles due to increasing environmental pollution and energy shortages.1,2 Compared with traditional lead–acid batteries, lithium-ion batteries have the advantages of a higher energy density and a longer cycle life and have gradually become the first choice for the power source of electric vehicles.3,4 However, after rapid charging and high-intensity discharging, lithium batteries generate a large amount of heat inside and on the surface of the battery. Because of the differences in the battery arrangement and energy capacity, a temperature gradient will be formed between the different batteries in the same battery pack, which causes the performance of the entire battery pack to become unstable,5–7 making its performance seriously limited by the working temperature. The ideal operating temperature of the lithium-ion battery is 20–40 °C.8,9 The maximum temperature difference (TD) between batteries in a battery string should not exceed 5 °C.10,11 When the battery temperature is too high, a series of safety accidents, such as fire and explosion, may occur.12 Therefore, the design and optimization of an efficient battery thermal management system (BTMS) to control the temperature and temperature difference (TD) of the battery pack within a narrow range is the key problem to be solved urgently.

Typical BTMSs include water cooling, air cooling, and phase-change material cooling.13 Based on these cooling methods, the relevant scholars have conducted a lot of studies. Among these cooling methods, air cooling is widely used because of its low cost and simplicity of structure.14 Mahamud15 designed a reciprocating air cooling structure for the heat dissipation of the battery pack, which has a very obvious effect on reducing the TD of the single cells in the battery pack. Xu16,17 reviewed the forced air cooling methods and simulated the heat dissipation performance of different airflow duct modes of the 55 A h battery pack. Zhang et al.18 illustrated that an adequate air flow rate of active cooling was required at high discharge rates and elevated temperatures for a practical thermal management system. Wang et al.19 added design to the battery module of the spoiler. The spoiler was installed at the battery clearance to verify the impact of different shapes, quantities, and lengths on the heat dissipation of the battery pack. Finally, the optimal scheme is determined, whose results are of important guidance for improving the Z-shaped air cooling performance and cost saving. Saw et al.20 mentioned that a high TD shortened the life of the battery module due to inconsistent cooling results.

In the above research, by changing the structure of the battery pack or increasing the flow the purpose of battery pack cooling was achieved. In this paper, under the condition that the total flow rate and the space structure of the battery pack are not changed, multiple inlets are set up, and the flow
distribution of different inlets is reasonable to achieve the purpose of reducing the maximum temperature of the battery module. This method is applied to the lithium battery pack with cell damage, and a fault-tolerant optimization method for the lithium battery pack with cell damage is proposed.

In this paper, a simulation method for a typical air-cooled lithium battery pack having a damaged unit was studied. Also, a fault tolerance optimization method for the lithium battery pack having a damaged unit was recommended based on the multi-island genetic algorithm.

2. MODEL AND PROBLEM DESCRIPTIONS

2.1. Model Description. In this study, a typical air-cooled lithium battery pack was researched under the condition of having a damaged unit.

Figure 1. 3D model of an air-cooled battery pack.

Figure 2. Grid for the total battery pack.

Figure 3. Grid for a single battery.

| item     | density: kg·m⁻³ | specific heat: J·(kg·K)⁻¹ | conductivity: W·(m·K)⁻¹ |
|----------|-----------------|---------------------------|-------------------------|
| battery  | 1958.7          | 733                       | \( k_x = 3.6, \ k_y = k_z = 10.8 \) |
| air      | 1.225           | 1006.43                   | 0.0242                  |

Table 1. Materials Properties

This paper uses UG software to build a battery pack model. The size of the battery cooling system is 230 mm × 73 mm × 175 mm, and the square lithium iron phosphate positive lithium-ion battery was selected as the experimental battery, with a size of 16 mm × 65 mm × 131 mm, a rated capacity of 10 A h, and a nominal voltage of 3.2 V. 10 lithium batteries are
arranged in the cooling system with an equal battery interval of 6 mm, and we call them 1 to 10 from left to right as shown in Figure 1. The total inlet size is 214 mm × 15 mm, and it is divided into four equal parts, which are, respectively, labeled 1, 2, 3, and 4. The size of the outlet of the cooling system is 214 mm × 15 mm too.

The simulation of air-cooling heat dissipation of the lithium-ion battery pack involves the heat conduction of the battery, air heat conduction, and fluid-structure coupling convection heat transfer between air and the battery surface and between air and the battery box surface. There are four groups of governing equations, which are the heat conduction control equations of the battery pack with an internal heat source, a continuity equation, a momentum equation, and an energy equation, respectively, as shown in eqs 1–4.

$$\rho_b C_b \frac{\partial T}{\partial t} = k_x \frac{\partial^2 T}{\partial x^2} + k_y \frac{\partial^2 T}{\partial y^2} + k_z \frac{\partial^2 T}{\partial z^2} + Q$$  \hspace{1cm} (1)

$$\frac{\partial \rho_{air}}{\partial t} + \text{div}(\rho_{air} \mathbf{u}) = 0$$  \hspace{1cm} (2)

$$\frac{\partial \mathbf{u}}{\partial t} + \text{div}(\rho_{air} \mathbf{u}) = \text{div}(\mu \text{grad} \mathbf{u}) - \frac{\partial p}{\partial t}$$  \hspace{1cm} (3)

$$\frac{\partial (\rho_{air} T_{air})}{\partial t} + \text{div}(\rho_{air} \mathbf{u} T_{air}) = \text{div}\left( \frac{K_{air}}{C_{air}} \text{grad} T_{air} \right) + S_T$$  \hspace{1cm} (4)

In formulas 1–4, $\rho_b$ is the battery density; $C_b$ is the specific heat capacity of the battery; $T$ is the electricity pool temperature; $t$ is the time of temperature change; $k_x$, $k_y$, and $k_z$ are the thermal conductivities of the battery in $x$, $y$, and $z$ directions, respectively; $Q$ is the heat generation rate per unit volume of the battery; $\rho_{air}$ is the air density; $\mathbf{u}$ is the air velocity vector; $\mu$ is the aerodynamic viscosity; $p$ denotes the air pressure inside the battery box; $T_{air}$ is the air temperature; $K_{air}$ is the thermal conductivity of air; $C_{air}$ is the specific heat capacity of air; and $S_T$ is the viscous dissipation term.

For simulating the air-cooled battery pack, we used simulation software ANSYS-FLUENT to obtain the temperature distribution of the battery pack. In this analysis, we calculated heat conduction, heat convection, and heat radiation. The $k-\varepsilon$ turbulence model was used for heat convection, and the discrete ordinate method was used for heat radiation. The heat source for each lithium battery was 21 kW/.

| no. | mean temperature (K) | maximum temperature (K) | minimum temperature (K) |
|-----|----------------------|--------------------------|--------------------------|
| 1   | 303.315              | 303.792                  | 301.817                  |
| 2   | 304.050              | 305.106                  | 302.263                  |
| 3   | 304.102              | 305.006                  | 302.340                  |
| 4   | 303.993              | 304.924                  | 302.322                  |
| 5   | 304.974              | 304.923                  | 302.244                  |
| 6   | 304.897              | 304.791                  | 302.349                  |
| 7   | 304.706              | 304.397                  | 302.204                  |
| 8   | 304.551              | 304.205                  | 302.111                  |
| 9   | 302.847              | 303.435                  | 301.628                  |

| no. | mean temperature (K) | maximum temperature (K) | minimum temperature (K) |
|-----|----------------------|--------------------------|--------------------------|
| 1   | 303.847              | 304.609                  | 302.367                  |
| 2   | 304.737              | 305.693                  | 302.819                  |
| 3   | 304.854              | 305.917                  | 302.953                  |
| 4   | 305.086              | 306.246                  | 303.110                  |
| 5   | 307.384              | 308.796                  | 304.823                  |
| 6   | 305.403              | 306.810                  | 303.150                  |
| 7   | 305.105              | 306.344                  | 303.160                  |
| 8   | 304.692              | 305.462                  | 302.919                  |
| 9   | 304.401              | 305.127                  | 302.743                  |
| 10  | 303.558              | 304.229                  | 302.162                  |

Figure 4. Temperature contour of the total domain for a normal case.
The velocity conditions for the four inlets were the same as 3 m/s, and the outflow condition was applied to the outlet. The boundary condition for the case of the cooling system was set as heat convection under the condition that the heat transfer coefficient and the air temperature were 5 W/(m$^2$·°C) and 298 K, respectively.

A simple algorithm and a second-order upwind scheme are used for the momentum equation, energy equation, continuity equation, and turbulent dissipation equation.

In this study, the total number of the grid was about 650,000, as shown in Figures 2 and 3.

Table 1 shows the material properties for the simulation model.

2.2. Problem Description. In this section, we discussed the critical problem of having a damaged unit. The no. 5 battery was assumed as the over-heated battery having a heat source of 36 kW/m$^3$.

As shown in Tables 2 and 3, the problem of having a damaged unit significantly affects the temperature distribution of the battery pack. Figures 4–7 show the temperature contours for the normal and damaged cases, which can obviously find out the change due to the damaged unit.

These figures can give us a chance to understand the phenomenon in the air-cooled battery pack.

As can be seen from the figure above, when the thermal power of battery no. 5 is increased as a damaged unit, the maximum temperature of the battery string rises from 305.2 to
308.8 K, resulting in an increase of 3.6 °C. At this time, the heat production and temperature of no. 5 battery are the highest. If no measures are taken, the performance and life of the entire battery pack will be affected.

3. CONSTRUCTION OF FITTING FUNCTION

3.1. Sensitivity Analysis. For the purpose of keeping the total flow unchanged, the inlet is divided into four, and different flow distributions are carried out on the four inlets to achieve the purpose of reducing the maximum temperature of the battery pack. Here, it can also be said that the temperature of the damaged unit battery is lowered to ensure the normal operation of the battery pack.

### Table 4. Sensitivity Analysis for the Velocity of Each Inlet

| no. | inlet 1 (m/s) | inlet 2 (m/s) | inlet 3 (m/s) | inlet 4 (m/s) | maximum temperature (K) |
|-----|---------------|---------------|---------------|---------------|--------------------------|
| 0   | 3             | 3             | 3             | 3             | 308.214                  |
| 1   | 1.8           | 3             | 3             | 3             | 309.512                  |
| 2   | 4.2           | 3             | 3             | 3             | 307.340                  |
| 3   | 3             | 1.8           | 3             | 3             | 306.926                  |
| 4   | 3             | 4.2           | 3             | 3             | 308.183                  |
| 5   | 3             | 3             | 1.8           | 3             | 308.444                  |
| 6   | 3             | 3             | 4.2           | 3             | 307.102                  |
| 7   | 3             | 3             | 3             | 1.8           | 309.249                  |
| 8   | 3             | 3             | 3             | 4.2           | 307.642                  |

Figure 7. Temperature section view for a damaged case.

Figure 8. Maximum temperature of the battery module.
In order to check the sensitivity of each inlet velocity to the temperature distribution of the battery pack, we changed each inlet velocity step by step.

We all know that the highest temperature of the battery module has the greatest impact on whether the battery works properly. Therefore, we decided to set the maximum temperature of the battery pack as the target value as shown in Table 4. Also, the velocity of each inlet was changed step by step under the condition of increasing or decreasing 40% compared to the original case (case 0) shown in Table 4.

As shown in Table 4, the maximum temperature of the battery pack changes obviously with the flow rate of no. 2 inlet. The maximum temperature of the battery module is shown in Figure 8.

### 3.2. Fitting Function

In this study, the velocities of inlet 1, inlet 2, and inlet 3 were selected as design variables. The velocity of inlet 4 can be obtained according to the velocities of Table 5. Upper and Lower Boundaries of Each Inlet Velocity

| item | inlet 1 (m/s) | inlet 2 (m/s) | inlet 3 (m/s) |
|------|---------------|---------------|---------------|
| upper | 3.9           | 3.9           | 3.9           |
| lower | 2.1           | 2.1           | 2.1           |

Table 6. Analysis Results of Selected Experimental Points

| sample | inlet 1 (m/s) | inlet 2 (m/s) | inlet 3 (m/s) | max temperature of the battery pack (K) |
|--------|---------------|---------------|---------------|----------------------------------------|
| 1      | 2.1           | 2.3           | 3.9           | 307.743                                |
| 2      | 2.2           | 3.7           | 2             | 307.143                                |
| 3      | 2.4           | 2.6           | 2.8           | 307.050                                |
| 4      | 2.5           | 2.8           | 3.5           | 307.962                                |
| 5      | 2.6           | 2.5           | 2.8           | 307.715                                |
| 6      | 2.9           | 3.9           | 3.2           | 309.059                                |
| 7      | 3             | 2             | 3.8           | 306.855                                |
| 8      | 3.1           | 3             | 2.3           | 307.706                                |
| 9      | 3.3           | 2.5           | 4             | 307.817                                |
| 10     | 3.4           | 4.2           | 2.5           | 308.965                                |
| 11     | 3.5           | 2.1           | 2.5           | 306.253                                |
| 12     | 3.6           | 3.5           | 2.1           | 308.494                                |
| 13     | 3.8           | 2.7           | 2.7           | 307.703                                |
| 14     | 3.9           | 1.8           | 2.1           | 305.836                                |
| 15     | 2.7           | 3.2           | 3             | 308.393                                |
| 16     | 2.1           | 2.9           | 3.1           | 308.747                                |
| 17     | 2.3           | 3.3           | 3.3           | 308.933                                |
| 18     | 2.5           | 2.5           | 2.7           | 307.505                                |
| 19     | 2.7           | 2.7           | 3.5           | 307.672                                |
| 20     | 2.9           | 2.3           | 3.9           | 306.995                                |
| 21     | 3.1           | 2.1           | 2.1           | 306.156                                |
| 22     | 3.3           | 3.9           | 2.9           | 309.104                                |
| 23     | 3.5           | 3.7           | 2.5           | 308.563                                |
| 24     | 3.7           | 3.1           | 3.7           | 308.100                                |
| 25     | 3.9           | 3.5           | 2.3           | 308.414                                |
| 26     | 2.4           | 3.6           | 3.6           | 309.639                                |
| 27     | 1.5           | 4.5           | 4.5           | 310.651                                |
| 28     | 3.6           | 2.4           | 2.4           | 306.563                                |
| 29     | 3.6           | 2.4           | 3             | 306.681                                |
| 30     | 2.4           | 2.4           | 2.4           | 306.742                                |
| 31     | 2.4           | 2.4           | 3.6           | 307.464                                |
| 32     | 2.4           | 3.6           | 2.4           | 307.949                                |
| 33     | 3             | 2.4           | 2.4           | 306.888                                |
| 34     | 2.4           | 2.4           | 4.8           | 307.553                                |
| 35     | 3             | 2.4           | 3             | 307.112                                |
| 36     | 2.1           | 2.9           | 2.5           | 307.875                                |
| 37     | 2.3           | 3.3           | 2.3           | 307.513                                |
| 38     | 2.5           | 3.9           | 2.1           | 308.036                                |
| 39     | 2.7           | 2.5           | 3.7           | 307.465                                |
| 40     | 2.9           | 3.5           | 2.9           | 308.616                                |
| 41     | 3.1           | 3.7           | 3.9           | 309.045                                |
| 42     | 3.3           | 2.3           | 3.3           | 306.886                                |
| 43     | 3.5           | 3.1           | 3.5           | 308.240                                |
| 44     | 3.7           | 2.1           | 3.1           | 306.625                                |

Table 7. Coefficients of Fitting Function

| item | calculated values |
|------|-------------------|
| a    | 298.852718642367  |
| b    | -0.4725469232696  |
| c    | 1.5663616963171   |
| d    | 3.35266925903145  |
| e    | 0.146174650127095 |
| f    | -0.297506983124169|
| g    | -0.340972215545617|
| h    | 0.299033702013059 |
| i    | -0.46885920252356 |
| j    | 0.206690366161485 |
inlet 1, inlet 2, and inlet 3 under the condition of fixing the total mass flow rate of all inlets at a certain value.

The upper and lower boundaries for the velocities of inlet 1, inlet 2, and inlet 3 are shown in Table 5 which are obtained by increasing or decreasing 30% based on the original value of 3 m/s.

Based on the Latin-hypercube sampling method, 44 experimental points were selected. Latin-hypercube sampling is a method of approximate random sampling from the distribution of multivariate parameters. It is a stratified sampling technique, and it is often used in computer experiments. In statistical sampling, the Latin-hypercube square matrix refers to a square matrix containing only one sample per row and column. Latin-hypercube is the generalization of the Latin-hypercube square matrix in multiple dimensions, and each hyperplane perpendicular to the axis contains at most one sample.

The target value of this study was set as the maximum temperature of the battery pack, and Table 6 shows the analysis results for the selected experimental points.

When establishing the second-order response surface model, the minimum number of samples is \((N + 1) \times (N + 2)/2\), where \(N\) is the number of test variables. There are three design variables in this article, and the minimum number of samples is 10. In order to establish a response surface model with high fitting accuracy, this paper uses the design of experiments (DOE) component of the iSIGHT platform to call ANSYS software to formulate a simulation experiment with 44 characteristic sample points. In this paper, 10 parameters are selected as design variables. During the response surface fitting process, a 44-term quadratic complete polynomial is established. The least square method is used to complete the fitting of the response surface model of each output response variable. The response surface approximate model of the highest temperature \(y\) of the battery pack is established.

A fitting function shown in eq 5 was used to construct the relationship between the objective and the design variables, where \(y\) is the objective function and \(x\) is the design variable.

\[
y = a x_1^2 + b x_2^2 + c x_3^2 + d x_1 x_2 + e x_1 x_3 + f x_2 x_3 + g x_1 + h x_2 + i x_3 + j
\] (5)

According to the analysis results shown in Table 6, the coefficients for the fitting function were calculated as shown in Table 7.

As the quality assessment value of the fitting function, \(R^2\) in this study was 0.93, which can tell us that the quality of the fitting function is high enough. The error between the prediction model results and the training model is shown in Figure 9.

The trend relationship between \(x_1\), \(x_2\), and \(x_3\) and the target value \(y\) can be observed in iSIGHT approximation model visualization, as shown in Figure 10. At the same time, we can see the relationship between the influence of \(x_1\), \(x_2\), and \(x_3\) on the target, as shown in Figure 11.

As can be seen from the figure above, the degree of influence on \(y\) is arranged in a descending order: \(x_2 > x_3 > x_1\); this is consistent with the preliminary inference in 3.1 sensitivity analysis, and the value of \(y\) increases with the increase of \(x_2\) and \(x_3\). The target value of \(y\) is the maximum temperature of the battery pack, so we should make the value of \(y\) as small as possible. A smaller value of \(x_2\) and \(x_3\) will have positive effects on reducing the maximum temperature.

4. OPTIMAL RESULTS AND DISCUSSION

4.1. Optimization Concept. The multi-island genetic algorithm is a parallel genetic algorithm based on grouping developed from the traditional genetic algorithm. The difference between the traditional genetic algorithm and the multi-island algorithm is that the multi-island genetic algorithm divides the entire population into several subgroups. The groups are isolated from each other on different islands, where each subgroup evolves independently instead of all the populations adopting the same evolution mechanism, and each island carries out a migration operation at a certain time.
interval so that each island’s multi-island genetic algorithm can effectively increase the speed of calculation; several independently evolved subgroups increase the genetic diversity of the entire population, so it can also avoid the premature phenomenon of traditional genetic algorithms, which is conducive to finding the global optimum untie. \(^\text{44–46}\)

In this study, the multi-island genetic algorithm was used to obtain the optimal mass flow rate of each inlet.

**4.2. Results and Discussion.** The number of subpopulations is 20, the number of islands is 10, the genetic generation number is 10, the crossover rate is 1, and the mutation rate and the migration rate are 0.01. After 2000 optimization iterations, the optimal solution is obtained.

After optimization, we can draw the contour of \(y \text{ vs } x_2, x_3\) as shown in Figure 12.

We can see that the low-temperature areas are concentrated in the lower left corner of the image, and the high-temperature areas are concentrated in the upper right corner. Therefore, to keep the temperature of the battery pack as low as possible, the values of \(x_2\) and \(x_3\) should be as low as possible; that is, the flow rate of inlet 2 and inlet 3 should be reduced.

\(\text{iSIGHT software was used to optimize the model. After optimization, when the flow velocity of inlet 1–4 is 2.5, 1.8, 1.8, and 5.9 m/s, respectively, the } y \text{ value of the obtained optimal solution is } 305.311 \text{ K. The optimal inlet velocity distribution results are input into FLUENT simulation software to verify the reliability of the prediction results. The simulation result shows that the } y \text{ value is } 305.905 \text{ K (32.755 } ^\circ \text{C). The temperature cloud diagram and the temperature section view diagram are shown in Figures 13 and 14. The result of the margin of error is small and can be ignored. The initial model shows that the flow velocity of the four inlets is 3 m/s, and the maximum temperature of the battery pack is } 308.796 \text{ K (35.646 } ^\circ \text{C). The optimized model is compared with the initial model, and the maximum temperature of the battery pack is dropped by 2.891 } ^\circ \text{C or 8.12%, thereby achieving the cooling optimization goal.}

From the temperature cloud map and the temperature distribution map of the cut surface, we can see that the heat originally concentrated in damaged cell number 5 is dispersed to the surrounding batteries. This solution not only reduces the maximum temperature of damaged cells but also makes the temperature distribution of the entire battery pack more uniform, which has a positive impact on improving the working performance and life of the battery pack. At the same time, this solution not only provides ideas for battery pack temperature control but, more importantly, also provides a fault-tolerant mechanism for battery cell damage. In practical work, when the internal resistance of a battery increases and the heating power increases due to the high temperature of the battery pack, this low-cost solution that does not change the space structure or increase the flow rate is used to maintain the battery pack. The stability of the work indicates that this is undoubtedly a very feasible solution.

**5. INFLUENCE OF DIFFERENT AMBIENT TEMPERATURES**

In order to explore the effect of ambient temperature on the heat dissipation performance of the battery pack, we increased

\[\text{Figure 12. Contour of } y \text{ vs } x_2, x_3.\]

\[\text{Figure 13. Temperature distribution of the optimal case.}\]
and decreased the original ambient temperature of 298 K by 5 K, respectively. The initial ambient temperature for the simulation is set to 293 and 303 K, respectively. The obtained temperature cloud diagram and temperature section view diagram are shown in Figures 15–18. The detailed temperature data are shown in Table 8.

When the initial ambient temperature is set to 293 K, the maximum temperature of the battery pack drops by 4.922 K compared to when the ambient temperature is 298 K. The magnitude of the drop is basically consistent with the drop in the ambient temperature, and the maximum TD of the battery pack remains almost unchanged at 4.616 K compared to the ambient temperature of 298 K.

When the initial ambient temperature is set to 303 K, the maximum temperature of the battery pack is 5.133 K higher than when the ambient temperature is 298 K. The magnitude of its rise is basically consistent with the rise in ambient temperature, and the maximum TD of the battery pack remains almost unchanged at 4.583 K compared to the ambient temperature of 298 K.

Combining the above charts, it is not difficult to find that when the initial ambient temperature is changed, the temperature distribution of the battery pack remains largely unchanged. The maximum temperature of the battery pack will show a basically consistent increase and decrease trend as the ambient temperature drops and rises, while the maximum TD of the battery pack remains basically unchanged. This also...
proves from the side that the thermal management system has considerable stability, and the heat dissipation performance is good.

6. CONCLUSIONS

In this study, we discuss a key issue that battery packs may face during operation, namely battery aging due to overcharge and discharge, which in turn causes damage to the battery cells. When this happens, the temperature of the unit cell will rise, causing the performance of the battery pack to decrease. In order to maintain the stability of the performance, we should take as many measures as possible to reduce the operating temperature and keep it within the normal operating temperature range.

This paper designs a multi-imported battery pack model. Under the condition of constant total flow, the airflow distribution of multiple air inlets is determined based on the Latin hypercube sampling method, and relatively acceptable design points are obtained by using the response surface fitting function combined with the multi-island genetic algorithm and other technologies. That is to say, when the flow rates of inlets 1–4 are 2.5, 1.8, 1.8, and 5.9 m/s, respectively, the temperature of the battery pack is the best, which achieves the optimal operating conditions and satisfies the requirements in the event of damage to the organic unit. The objective of
controlling the TD and temperature rise under the given circumstances is that the simulation and optimization methods developed in this study will be widely used to confirm the operational reliability of the system, providing new ideas for the resolution of such situations.

**AUTHOR INFORMATION**

**Corresponding Author**

Zhenzhe Li – College of Mechanical and Electrical Engineering, Wenzhou University, Wenzhou 325035, China; orcid.org/0000-0003-3356-2416; Phone: +86-577-8668-9177; Email: a13868659593@163.com; Fax: +86-577-8668-9166

**Authors**

Fusheng Gu – College of Mechanical and Electrical Engineering, Wenzhou University, Wenzhou 325035, China

Zhenmu Chen – College of Mechanical and Electrical Engineering, Wenzhou University, Wenzhou 325035, China

Ming Wang – College of Mechanical and Electrical Engineering, Wenzhou University, Wenzhou 325035, China

Complete contact information is available at:
https://pubs.acs.org/10.1021/acsomega.2c03329

**Notes**

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**NOMENCLATURE**

$x$, design variable; $y$, objective function; $R^2$, assessment value for fitting function

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