INTRODUCTION

Approximately 40% of the energy in traditional cars is discharged into the air through exhaust gas, causing a lot of waste of thermal energy, leading to huge economic losses.1-3 Thermoelectric generators (TEGs) are the devices that can convert thermal energy into electrical energy, which can effectively achieve energy recovery.4,5 Usually, the recovered electric energy is stored through a battery pack and is supplied to the vehicle-mounted electrical equipment.6

The battery management system, as the core of battery monitoring, is widely used in electric vehicles. In software design, a reasonable algorithm is used to achieve battery state estimation and energy balance, which have a very important impact on vehicle safety.7-12 But the system hardware structure design is also important, because the temperature of the battery pack rises during charging and discharging, the temperature between different batteries will cause the temperature in the battery pack to be inconsistent, and ultimately affect the life of the power battery.13-15

Abstract

Traditional automobile exhaust contains a large amount of thermal energy. Thermoelectric generators (TEGs) can store recovered electrical energy into battery packs and supply to vehicle-mounted electrical equipment. A reasonable battery pack structure is designed to facilitate stable vehicle operation based on the actual conditions of the vehicle. This paper presents investigation on thermal performance of air-cooled li-ion battery pack in different arrangements. Taking the AVIC (Aviation Industry Corporation of China) lithium battery as the research object, a battery pack model based on T-type parallel ventilation structure is established in Fluent, and the accuracy of the model is verified through experiments. In the same battery module, there are three typical arrangements of forming battery cells into an equal arrangement, an increasing arrangement, and a decreasing arrangement. The changes of the temperature field of the battery pack under different discharge rates and wind speeds are studied, respectively. Studies have found that battery pack arranged in decreasing order has the best temperature consistency and the temperature difference is reduced by 14.82% and 6.21%, respectively, at 1C and 2C discharge rates, compared to the equally spaced arrangement.

KEYWORDS
air cooling, lithium-ion battery, structural optimization, temperature uniformity
In recent years, a lot of attention has been paid to the thermal management system of battery, which can be divided into active thermal management system and passive thermal management system. The former is to uniform the battery pack temperature by forced convection of air or coolant, while the latter is to reduce the battery pack temperature by natural convection, phase change material and other means. Comprehensive cost, tightness and other factors, air cooling is one of the best way to achieve cooling efficiency.

Tairan Yang et al. studied the thermal performance of axial air cooling of lithium-ion battery pack, found increasing radial interval could reduce the average temperature rise. Haoting Wang et al. proposed a simple switching control strategy, which could effectively reduce the parasitic power consumption of cooling system under the evaluation of ambient temperature by opening and closing the single-side air supply device, even if the lithium-ion battery was under dynamic load. A study by Liwu Fan et al. found that reducing air gap spacing and/or increasing Fan flow would reduce the maximum temperature rise. Under the same air gap spacing and air volume, the effect of unilateral cooling was worse than that of bilateral cooling. Rajib Mahamud et al. studied a heat management method of reciprocating air flow to improve the temperature uniformity of electric vehicle batteries and reduce the maximum temperature of batteries. Fan He et al. established a reduced-order model on the basis of Rajib Mahamud, combined the active temperature control strategy with the reciprocating air flow, and the simulation results showed that the temperature inhomogeneity between units and the required cooling flow could be significantly reduced. Kai Chen et al. conducted an in-depth analysis and optimization of the inlet and outlet locations of the battery thermal management system, and found that higher cooling located in the middle of the static chamber. Taking z-type parallel air-cooled battery as an example, an algorithm to optimize the spacing between the battery packs was proposed, which improved the cooling effect without changing the power consumption.

Previous studies have shown that battery spacing, air inlet and outlet positions, and control strategies all have a significant impact on the temperature difference and maximum temperature rise of the battery pack. However, taking thermoelectric power generation as the object and combining the specific structure of the vehicle to design a reasonable battery pack thermal management system remains to be studied. In this paper, three typical battery pack layouts for T-shaped parallel ventilated spaces are designed, and a battery model is built using Fluent and the temperature field is studied.

The framework of this paper is as follows. The structure of the battery pack and the modeling method is introduced in Section 2. In Section 3 the cell model is tested by experiment to ensure that the model was accurate and reliable. The change of temperature field of battery pack models is studied with different arrangement orders under different wind speeds in Section 4. The conclusion is made in Section 5.

2 | INTRODUCTION

2.1 | Problem description

As shown in Figure 1, the exhaust gas from the engine generates electricity through the TEG device, and the electric energy is stored in the battery pack through the DC/DC converter. The vehicle continuously charges the battery pack during the driving process, and when needed, the battery pack can realize electric energy output to the vehicle-mounted electrical equipment. Reasonably setting the structure of the battery pack is conducive to maintaining the uniformity of the temperature of the battery pack and the long-term stable operation of the battery. In practice, the peak power of TEG device can reach 1000 W and 12 single AVIC lithium batteries with a nominal capacity of 40 Ah and a charge-discharge voltage of 2.0 V-3.6 V are selected to complete energy recovery. According to the actual vehicle structure, this paper designs the battery pack as a T-type ventilation structure.

Figure 2 shows the structure of the battery thermal management system (BTMS). The cooling air enters from the middle of the battery pack and sent by the air outlets at both ends. The flow of air will take away the heat of the single battery, so that the temperature of the entire battery pack is maintained at a suitable working temperature, but the spacing between the individual batteries will affect the wind speed
and result in difference in temperature. Therefore, in a given battery module, the use of a suitable arrangement of battery packs will improve the consistency of the temperature field within the battery pack and improve overall performance. Thermal property parameters of AVIC lithium cell are shown in Table 1.

### Table 1 Thermal property parameters of AVIC lithium cell

| Member   | Ingredient                                      | Density (kg/m³) | Specific heat (J/kg) | Thermal conductivity (W/m K) |
|----------|-------------------------------------------------|-----------------|----------------------|-------------------------------|
| Kernel   | Copper, aluminum, lithium iron phosphate, graphite, electrolyte, etc | 2173            | 895                  | 1.1 (x direction) 18.3 (y, z direction) |
| Air gap  | Air                                             | 1.225           | 1006                 | 0.024                         |
| Negative pole | Copper                                      | 8900            | 385                  | 398                           |
| Positive pole | Aluminum                                      | 2700            | 903                  | 238                           |
| Shell    | Nylon                                           | 1180            | 1500                 | 0.35                          |
| Top cover | Nylon                                          | 1180            | 1500                 | 0.35                          |
| Nut      | Aluminum                                       | 2700            | 903                  | 228                           |

### 2.2 Grid model

Meshing divides the fluid and fluid area around the battery into several submodules. In order to facilitate data collection and simplifying the difficulty, the meshing should adhere to the principle of high mesh density and large number of meshes. It is usually necessary to perform hybrid mesh processing on complex models. For this design model, the single cell and the battery module can be structured and meshed. Because the cell is relatively regular and simple, 52,331 grids are generated by automatic grid generation, and the grid number of battery box is 6,413,569. Let T1-T6 be the temperature collection points, which are the temperatures of the same side battery shown in Figure 3B.

### 2.3 Battery thermal model

#### 2.3.1 Selection of thermal model

In order to achieve a comprehensive, safe and stable energy output, a detailed 3D thermal model is selected for analysis. The internal reaction and thermal effects of lithium-ion cells are complicated and need to be simplified from the following aspects.

1. Treat the inside and outside of the battery pack as a unified whole, and the relevant parameters of each part of the battery are unified, and the coefficients are stable under different working conditions of the battery.
2. The thermal conductivity of the battery is equal in the same radial direction, and remains unchanged in the case of temperature and SOC changes.
3. The physical structure and material texture of the active electrode material are uniform, and the heat generation rate is consistent under the condition of constant current charge and discharge.
4. Since the transport of substances in the electrolyte passes through diffusion and migration at an ideal external
temperature, only heat conduction factors are considered, and the temperature jitter caused by heat convection, heat radiation, side reaction heat, and self-heating of the controller itself is ignored. Therefore, the battery thermal model is as follows:

\[
\rho C_p \frac{dT}{dt} = \lambda_x \frac{\partial^2 T}{\partial x^2} + \lambda_y \frac{\partial^2 T}{\partial y^2} + \lambda_z \frac{\partial^2 T}{\partial z^2} + Q
\]  

(1)

\[Q_{\text{core}} = \frac{1}{V_{\text{core}}} \left( \dot{I}^2 R_{\text{core}} + IT \frac{dU_0}{dT} \right) \]  

(2)

\[Q_{\text{pole}} = \frac{\dot{I}^2 R_{\text{pole}}}{V_{\text{pole}}} \]  

(3)

\[V_{\text{core}} \text{ is the volume of the battery core, } R_{\text{core}} \text{ the internal resistance of the battery, } R_{\text{pole}} \text{ the resistance value of the battery pole, } V_{\text{pole}} \text{ the volume of the battery pole. The initial temperature and ambient temperature of the model are both 25°C, and the thermodynamic temperature is 298 K. The open circuit voltage measured by the experiment changes little with the temperature, and the average value is taken according to the test results, in the calculation, the temperature influence coefficient is treated as a fixed value 0.5 mV/K.} \]

\[Q = Q_{\text{core}} + Q_{\text{pole}} = 1013 \dot{I}^2 f(SOC) + 25.96 \dot{I}^2 + 14.5 \dot{I} \]  

(4)

In the actual test, the internal resistance does not change much in the temperature range. The curve fitting calculation of the internal resistance with the change of SOC at 25°C is as follows:

\[f(SOC) = 0.211 SOC^6 - 0.75 SOC^5 + 1.06 SOC^4 - 0.76 SOC^3 + 0.29 SOC^2 - 0.06 SOC + 0.0065 \]  

(5)

When the battery is discharged at a constant rate, the relationship between SOC and time can be described as follows:

\[SOC = 1 - \frac{It}{3600C} \]  

(6)

\(I\) is the current at battery operation, \(t\) is discharge time for battery, \(C\) is the battery capacity. According to the above three formulas, the relationship between the volume heating power and the discharge time of the battery can be obtained, and the time-varying heat source of the battery model can be obtained.

### 2.3.2 Volume heating power of the battery

The battery and the pole are the heat sources of the battery. To calculate the heat generation rate of the battery, it is necessary to determine the current intensity and the internal resistance of the battery when it is working. The internal resistance of the battery changes with the change of SOC, while the SOC and the discharge time of the battery can be calculated mathematically. Therefore, the mathematical relationship between the internal resistance of the battery and the discharge time can be obtained through the fitting of the internal resistance curve with the change of SOC, which is brought into the heat generation formula, it can simulate the heat generation of the battery at all times in the discharge process.

### 2.4 Calibration of thermophysical parameters

The specific pressure of the battery is related to its SOC, operating conditions and external temperature. The heat source of the battery mainly depends on the raw materials of the battery and the electrochemical reaction characteristics. The
heat capacity of the single cell can be calculated by mass weighting method, and then multiplied by the number of cells to obtain the heat capacity of the battery pack.

\[ C_p = \frac{1}{m} \sum_{i=1}^{n} C_i \times m_i \]  

(7)

\( C_p \) is the average constant pressure specific heat capacity of the single cell; \( m \) is the total mass of the single cell; and \( C_i \) and \( m_i \) are the specific heat capacity and mass of different materials inside the single cell.

The battery density can be obtained by the ratio of the total mass to the total volume of the battery module:

\[ \rho = \frac{M}{V} = \frac{\sum_{i=1}^{n} m_i}{\sum_{i=1}^{n} V_i} \]  

(8)

\( M \) is the total mass of the battery and \( V \) is the total volume of the battery. Among the three heat transfer modes inside the battery, heat convection and heat radiation have little effect on the battery module. In order to reduce the difficulty of modeling, the heat transfer effect can be neglected. Because the internal structure of the battery is made up of different materials, the \( x \)-axis is perpendicular to the positive and negative plates of the battery, and heat is transferred in series along the \( X \) axial positive and negative plates, and in the radial direction of the \( Y \) and \( Z \) axes, heat is transferred to the positive and negative plates in parallel. The formula is as follows:

\[ \lambda_x = \frac{l}{\sum_i \lambda_i} \]  

(9)

\[ \lambda_y = \lambda_z = \frac{\lambda_i dx_i}{l} \]  

(10)

In the above formula: \( dx_i \) is the thickness of each material in \( X \) direction. \( \lambda_i \) is the thermal conductivity of the each material of the battery; \( l \) is the lengths of the battery in the \( X \) directions. The parameter values related to the above calculation are listed in Table 2.

2.4.1 Fixed solution conditions

In a certain domain, the ambient temperature field distribution in the battery forms a function of working time and internal space, which is a dynamic process that changes with time and space.

1. Initial conditions

\[ T(x, y, z, 0) = T_0 \]  

(11)

The initial temperature of the battery can be set according to the outdoor temperature and the experimental temperature. In addition, the positive and negative material concentrations and electrolyte concentrations need to be set.

2. Boundary conditions

The thermal model boundary conditions are determined according to the temperature difference between the outer surface of the battery and the outside world and the convective heat transfer coefficient. Newton’s law states:

\[ -\lambda_x \frac{\partial T}{\partial x} = a \left(T - T_\infty\right), \quad x = 0 \text{ and } l \]  

(12)

\[ -\lambda_y \frac{\partial T}{\partial y} = a \left(T - T_\infty\right), \quad x = 0 \text{ and } b \]  

(13)

\[ -\lambda_z \frac{\partial T}{\partial z} = a \left(T - T_\infty\right), \quad x = 0 \text{ and } h \]  

(14)

In the above formula: \( a \) is the heat transfer coefficient between the surface of the battery and the outside; \( T_\infty \) is the temperature of the surrounding external environment; \( T \) is the surface temperature of the battery; \( l, b, \) and \( h \) is the length, width, and height of the battery, respectively; and \( \lambda \) is the thermal conductivity of the surface of the battery.

3 SINGLE CELL SIMULATION VERIFICATION

From the analysis of the temperature rise of the single cell, the design scheme can be better improved to ensure the reliability of the experiment. In order to investigate the temperature distribution of the lithium-ion battery in detail, set up the battery charging and discharging platform as shown in Figure 4, complete the battery charging and discharging experiment, and use an infrared thermometer to complete the temperature

### Table 2 Core material thickness and thermal conductivity

| Material     | Positive pole | Negative pole | Separator | Copper foil | Aluminum foil |
|--------------|---------------|---------------|-----------|-------------|---------------|
| \( dx_i (\mu m) \) | 19.9          | 21.6          | 3.46      | 1.3         | 1.3           |
| \( \lambda_i (W/m K) \) | 1.48          | 1.04          | 0.38      | 398         | 238           |
measurement of the battery. The Tp1-Tp5 temperature detection point is set at the four corners and the middle of the lithium battery to analyze the temperature distribution of the single cell, as shown in Figure 3A. It is convenient to verify the accuracy of the simulation model and provide a basis for the subsequent rational arrangement of the cooling wind flow path.

In Fluent, the 1C, 2C, and 3C discharge temperature simulations are performed on the single cell, and the same five points is collected in the same external environment and at appropriate time points. Therefore, the temperature field is analyzed with time.

Shown in Figure 5 is the temperature field distribution at 1C discharge rate at different times. At the same discharge rate, the positive and negative ear first heats up at the initial stage of discharge, and the temperature in the middle part is low. With the progress of the discharge process, the overall temperature of each part of the battery increases, but the middle part of the battery increases more obviously, which is always higher than the positive and negative electrode ears.

In order to clearly describe the temperature distribution law of the single cell, the highest temperature of the five points Tp1-Tp5 at 1C, 2C and 3C is averaged and indicated by a line graph in Figure 6. The highest temperature zone appears in the center of the battery, the temperature gradually decreases along the center, and the temperature in the lower part of the battery is higher than the temperature in the upper part of the battery. Therefore, when arranging the air inlet of the battery pack, it should be closer to the middle of the single cell.

The cell is tested for discharge at 1C, 2C, and 3C, and the temperature at T3 is collected by an infrared thermometer. The error curves of the simulation and experimental data are shown in Figure 7, showing the error changes at three different discharge rates.
The simulation temperature is slightly higher than the experimental temperature. The main reasons are as follows: in the simulation, the influence of heat radiation and air flow is neglected and the infrared thermometer takes the temperature from the outside to the inside, the temperature of the battery case is lower than the internal temperature of the battery. The error increased with the increase of time and discharge rate. This was because the neglected factors in the simulation should be more intense in the experiment as the temperature increases. Even when the battery is at 64.7 degrees, the error does not exceed 3.5%. The simulation results are in good agreement with the experimental results and could accurately reflect the temperature rise characteristics of the single cell.

4 | ANALYSIS AND DISCUSSION

The 12 cells are arranged in the same interval in the battery pack as Model 1 and 5 mm spacing between cells. Without changing the overall length of the battery module, just change the spacing between the cells in the horizontal direction. The battery spacing is based on the air inlet battery spacing (3 mm), and the battery spacing on both sides is increased by the equal difference (0.4 mm) as Model 2. The battery spacing is based on the air inlet battery spacing (7 mm), and the battery spacing on both sides is decreased by the equal difference (0.4 mm) as Model 3.

4.1 | Temperature field distribution in the battery pack

The forced convection is carried out at five different wind speeds of 3 m/s, 4.5 m/s, 6 m/s, 7.5 m/s and 9 m/s at three different discharge rates of 1C, 2C and 3C. The temperature fields of Model 1, Model 2, and Model 3 obtained at different times are analyzed.

At different discharge rates and wind speeds, the temperature division of the cells in the same battery array arrangement is highly consistent. Therefore, taking the battery temperature distribution at 1C discharge rate and 6 m/s wind speed as an example, the temperature field distribution of three models at 3600 seconds was analyzed.

It can be seen from Figure 8 that in the Model 2, the temperature of the single cell facing the tuyere is the lowest, gradually increasing to both sides. The temperature of the cell in the penultimate cell is the highest, and the difference between the cells in the battery pack is the largest. The temperature difference of the cell is the smallest. Under the arrangement of Model 2, the temperature difference of the cell is between Model 1 and Model 3.

In the three groups of models, the temperature in the middle of the battery is lower, because the temperature of the wind is lower at the air inlet. The two cells in the middle of the Model 2 have the smallest gap, which causes the wind speed in the gap to increase, causing more heat to be taken away; therefore, the temperature difference of the single cell in Model 2 is the largest. The arrangement of the batteries in Model 3 results in the wind speed gradually increasing to both sides, but at the same time, the wind temperature also slightly increases, and the overall temperature difference is the smallest.

4.2 | Maximum temperature difference of models

The relationship between the maximum temperature difference of the battery pack under the three battery packs

FIGURE 8  Temperature field distribution of 3600 s at 1C discharge rate (A) Model 1, (B) Model 2, and (C) Model 3
and the wind speed at different discharge rates is shown in Figures 9-11.

In Model 1, the trend of maximum temperature is presented in Figure 9. The discharge rate of battery 1C and 2C is lower. With the increase of wind speed, the temperature difference shows an upward trend, but the stability of the temperature difference is stable at 0.3 degrees. When the battery is discharged at 3C, the heat production surges and is more sensitive to changes in wind speed, so the temperature difference changes greatly.

Maximum temperature difference of Model 2 is shown in Figure 10. When the battery is at 1C discharge rate, the heat release is small. In Model 2, the intermediate battery gap is small resulting in faster flow and ventilation, and can take enough heat. Therefore, when the wind speed increases from 3 m/s, the temperature change of the middle battery pack is small, and the temperature drop of the battery on both sides is more significant resulting in a gradual decrease in the temperature difference.

When the battery is at 2C discharge rate, the heat generation of the cell increases, and the increase of the wind speed can lower the temperature of all the single cells. But the intermediate battery interval is small, which will cause the wind speed to increase and lead to an increase in temperature difference. When the wind speed continues to increase, the wind speed of the cell interval in the middle of the battery pack has reached the current heat balance, and the external wind speed continues to increase, which has less influence on the temperature change. The temperature of the single cell at both ends of the battery pack gradually decreases, resulting in a decrease in temperature difference.

When the battery is at the 3C discharge rate, the discharge rate of the battery is further increased. The heat generation rises rapidly and the increase of the wind speed can always take away more heat, so that the temperature difference is gradually rises.

The arrangement of Model 3 makes the temperature distribution of the battery pack more uniform, as is shown in Figure 11. Under different discharge rate, the maximum temperature difference of the battery pack changes little with the wind speed, and it is better than the temperature difference of Model 1 and Model 2.

### 4.3 Maximum temperature comparison

With the increase of wind speed level, the maximum temperature of battery pack would decrease. The higher the discharge rate is, the more obvious the temperature will decrease. Among them, the maximum temperature in Model 1 is greatly affected by constant speed, and the temperature drop 4.8
degrees at 3C discharge rate, as is shown in Figure 12. Under three discharge rates, the highest battery temperature in Model 1 is the lowest. The battery temperature of Model 2 is the highest, and that of Model 3 is between the two models. However, under the three arrangements, the highest temperature in each model is almost the same, basically within 1.8 degrees.

4.4 Minimum temperature comparison

Due to the increase in wind speed, the minimum temperature of the battery pack would decrease. The lowest temperature of Model 2 is the most affected by wind speed, and the temperature drop is 5.26 degrees, as is shown in Figure 13. From the overall downward trend of each model, the lowest temperatures of Model 1 and Model 2 are basically the same, and the temperature of Model 3 is always the highest at the three discharge rates, which is within 2 degrees of the temperature of other models under the same experimental conditions, and is affected by the wind speed smaller.

4.5 Experimental verification

Perform thermal management performance test based on Itech’s ITS5300 test platform, as is shown in Figure 14. This platform can perform constant voltage, constant current, and constant power charge and discharge tests on battery packs, and meets battery pack test requirements. The test bench discharges the battery pack at specific discharge rates and changes the wind speed level by adjusting the wind speed of the cooling fan.

The temperature measurement unit is arranged on 12 batteries, and the temperature data of 1C discharge and 2C discharge are measured, respectively. The results of Model 1 under the wind speed of 6 m/s are compared with the simulation results, and the error analysis is shown in Figure 15. The overall error value is very high that of the single cell in Figure 7, and the peak error is about 4.5%. The simulation results are consistent with the experimental results.

Under different wind speed and discharge rate, take the average value of temperature at the end of discharge of 12 single batteries, as shown in Figure 16. At 1C discharge...
rate, the temperature of Model 3 is always higher than that of Model 2. At 2C discharge rate, the temperature difference between Model 3 and Model 2 is not significant. At two discharge rates, the average temperature of Model 1 is the lowest. The maximum temperature difference of the three models is 2.3°C and 2.7°C, respectively. However, the average temperature of the three models is still within the normal operating range of the battery.

Figure 17 shows the temperature difference between the cells in the battery pack under different wind speeds and two discharge rates. At the discharge rates of 1C and 2C, the temperature difference of Model 1 and Model 2 increase with the increase of wind speed. The temperature consistency of Model 2 is poor, and the relationship between temperature difference and wind speed is not obvious. Under the two discharge rates, the temperature consistency of Model 3 is the best, compared with Model 1, the temperature difference is reduced by 14.82% and 6.21%.

Because the average temperature and the maximum and minimum temperature of the cell in the three models are within the normal temperature range of the battery, Model 3 is superior to Model 1 and Model 2 in terms of temperature consistency in the battery pack, which can make the battery pack work more reliably.

5 | CONCLUSION

In this paper, a T-type parallel ventilation structure of 12 AVIC lithium batteries is designed with the target of thermoelectric power generation and the actual conditions of the vehicle. The characteristics of the temperature distribution of battery pack are analyzed by changing the wind speed level and the arrangement of the cells. Without changing the overall length of the battery module, battery module with air inlets as the reference quantity, arranged on the two sides in the form of reduced equal difference, perform best in terms of temperature consistency and temperature of the single cells in the battery pack are within the normal operating range.

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ORCID

Changjun Xie https://orcid.org/0000-0002-9626-0813
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