INTRODUCTION

In recent years, the problems of environmental pollution and resource shortage have become increasingly serious, electric vehicles attach great importance because of their low energy consumption and low noise pollution.1,2 As the main power source of electric vehicles, the battery pack is composed of multiple cells arranged closely in series and parallel to obtain the desired voltage and capacity, so the heat generated during operation is difficult to be released, which result in the dangerous temperature of the battery pack.3-5 Therefore, the favorable battery cooling structure plays a very important role in the electric vehicle industry.1,4,5

Effects of air cooling structure on cooling performance enhancement of prismatic lithium-ion battery packs based on coupled electrochemical-thermal model

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Abstract
The increasing temperature of lithium-ion batteries during charging and discharging affects its operational performance. The current studies mainly adopt simplified model, less considering the effect of the battery internal electrochemical reaction on the air cooling performance, and the air cooling structure needs to be further optimized. In order to solve the problems above, the coupled electrochemical-thermal air cooling model was established, and the air cooling structure was optimized in terms of the relative position and height of the battery pack inlet and outlet, the distribution, and spacing of cells. The results show the better air cooling performance is achieved when the inlet and outlet are aligned on the same side. When the lateral inlet and outlet aligned on the same side, the lower outlet height is more important for improving the heat dissipation performance of the battery pack, but the worse temperature uniformity emerges. According to the cooling performance of different positions in the battery pack, a method for nonequidistant symmetrical distribution of cells is able to improve the temperature uniformity. The optimal combination of the air cooling structure with various factors is obtained.

KEYWORDS
air cooling performance, lithium-ion battery pack, nonequidistant symmetrical distribution, relative position and height of inlet and outlet

1 INTRODUCTION

In recent years, the problems of environmental pollution and resource shortage have become increasingly serious, electric vehicles attach great importance because of their low energy consumption and low noise pollution.1,2 As the main power source of electric vehicles, the battery pack is composed of multiple cells arranged closely in series and parallel to obtain the desired voltage and capacity, so the heat generated during operation is difficult to be released, which result in the dangerous temperature of the battery pack.3-5 Therefore, the favorable battery cooling structure plays a very important role in the electric vehicle industry.1,4,5

Abbreviations: 1D, one-dimensional; 2D, two-dimensional; 3D, three-dimensional; EV, electric vehicle; HEV, hybrid electric vehicle; PCM, phase change material; OCV, open circuit voltage; SOC, state of charge; ECM, electromagnetic compatibility; BMS, battery management system; BTMS, battery thermal management system.
role in reducing the maximum temperature of the battery pack and maintaining temperature difference of each battery within an appropriate range.\textsuperscript{6-8}

The current cooling methods of battery packs include air cooling,\textsuperscript{9-11} liquid cooling,\textsuperscript{12-15} phase change material cooling,\textsuperscript{16-20} and heat pipe cooling.\textsuperscript{21-23} Air cooling is widely used because of its simple structure, low cost, and lightweight. So more scholars dedicated to find advanced strategies for optimizing air cooling and simplifying air cooling structure. Wang et al.\textsuperscript{25} found that compared with different arrangements, the axisymmetric arrangement can obtain better forced air cooling performance. The symmetrical systems achieve much better cooling performance than the corresponding asymmetrical ones was found by Chen et al.\textsuperscript{27} Hong et al.\textsuperscript{28} proposed that setting the secondary vent at the farthest position away from the original outlet is also an effective way to improve the air cooling performance. The maximum temperature can be reduced by 5K or more, and the temperature difference can be reduced by 60% or more. The asymmetric inlet and outlet on both sides of the battery pack was designed by Jiaqiang et al.\textsuperscript{29} to reduce the maximum temperature and added baffle or shunt in the battery pack to improve the temperature uniformity. Yuqian Fan et al.\textsuperscript{30} showed that compared with the cross and staggered arrangement, the aligned arrangement of cells can improve the temperature uniformity and reduce 23% energy consumption under the same conditions. An orthogonal optimization method Jinghong was adopted by Xie et al.\textsuperscript{31} to analyze the effect of each parameter comprehensively such as inlet and outlet angles, cell spacing. When the inlet and outlet angles are 2.5° and the cell spacing is equal, the maximum temperature and temperature difference of the battery can be reduced by 12.82% and 29.72%, respectively. Jiaqiang et al.\textsuperscript{31} established the physical and mathematical models for a battery module with sixteen lithium-ion batteries, and the best cell arrangement structure and ventilation scheme were obtained based on the combination of orthogonal experiment design method and fuzzy gray relation theory.

Besides, more coupled electrochemical-thermal models of lithium-ion batteries were proposed and focused on the heat generation of single battery during charging and discharging.\textsuperscript{32-40} Xu et al.\textsuperscript{32} proposed a coupled electrochemical-thermal model to realize the interaction between electrochemical reaction and heat transfer of prismatic lithium-ion battery, the results indicated that the discharge uniformity of lithium battery is better when the electrode ears are evenly distributed on both sides. A coupled 1D electrochemical and 2D heat transfer air cooling model was established by Yang et al.\textsuperscript{33} to analyze the effects of distribution and space on the air cooling performance of cylindrical lithium-ion battery packs. A thermal model was established by Kim et al.\textsuperscript{37} to study the effect of the electrode configuration on the thermal behavior of a lithium-polymer battery, and based on the results of the modeling of potential and current density distributions, the temperature distributions of the lithium-polymer battery were calculated. Jingwei et al.\textsuperscript{38} proposed a coupled electrochemical-thermal model of the lithium battery, the results indicated that the appropriate increase of the heat dissipation in the middle of the battery is useful for the reduction of the central temperature inside the battery. Mevawalla et al.\textsuperscript{39} compared the experimental temperature and electrochemical-thermal model temperature for battery cell, analyzing the temperature distribution at different discharge rates.

The previous studies on the air cooling system of the battery pack have laid the foundation for future research, but the relative position and height of the inlet and outlet, the distribution, and spacing of the cells according to the cooling performance of different positions need to be further studied. Furthermore, previous studies mainly adopted the battery heat generation model, ignoring internal electrochemical reaction and the influence of the electric field distribution on the temperature, which greatly reduced the calculation amount, but cannot truly reflect the battery pack air cooling performance. Although the electrochemical-thermal model of lithium batteries has been proposed, the current studies mainly focused on the material and electrode lug position design of single battery and rarely applied electrochemical-thermal models in the air cooling system into the prismatic battery pack.

In this paper, a coupled electrochemical-thermal air cooling model of lithium-ion battery pack was established to improve the simulation accuracy. Moreover, the effect of inlet and outlet relative position and height on air cooling performance were analyzed. At last, the cell distribution and spacing were adjusted to improve the temperature uniformity. The air cooling structure of the battery pack was optimized by integrating various parameters.

The paper organized as follows: Model and verification were introduced in Section 2. Section 3 presented the influence of the relative position and height of inlet and outlet, the spacing, and distribution of cells on air cooling performance, and conclusions were made in Section 4.

2 | MODEL DEVELOPMENT

2.1 | Research schemes

The research adopts the prismatic LiFePO4 battery, and only one of the independent battery packs is simulated and analyzed in this study, which does not affect the results. In order to study the effect of the relative position of the inlet and outlet on cooling performance, there are 8 schemes of air cooling structure are selected as shown in Table 1 Research schemes of air cooling structure, where structure a represents
TABLE 1 Research schemes of air cooling structure

| Scheme       | Longitudinal | Lateral |
|--------------|--------------|---------|
|              |   |         |
| Different side | a | b       | c        | d        |
| Same side     | a’ | b’      | c’       | d’       |

![Diagram of research schemes](image)

FIGURE 1 Schematic graph of the one-dimensional cell in the prismatic LiFePO4 battery

longitudinal inlet and outlet align on the different sides, structure a’ represents longitudinal inlet and outlet align on the same side, structure b represents lateral inlet and outlet align on the different sides, structure b’ represents lateral inlet and outlet align on the same side, structure c represents lateral inlet and outlet cross on the different sides, structure c’ represents lateral inlet and outlet cross on the same side, structure d represents lateral inlet and outlet diagonalize on the different sides, and structure d’ represents lateral inlet and outlet diagonalize on the same side.
2.2 Coupled model

2.2.1 Coupled electrochemical-thermal model

The coupled electrochemical-thermal model describes the heat generation process of the LiFePO4 battery by the electrochemical reaction formula. The heat generation rate applied to the 3D (three-dimensional) thermal model to affect the battery interior temperature is calculated by the 1D electrochemical model. At the same time, the average temperature of the battery is in turn used in the 1D electrochemical model as the electrochemical reaction temperature, so as to realize the interaction between the electrochemical and heat transfer of the LiFePO4 battery. The type LP2065120 prismatic LiFePO4 battery was developed by the commercial finite-element software COMSOL Multiphysics 5.4. The nominal voltage and capacity of the cell are 3.2 V, 12.3 Ah, respectively. The computational domain of the 1D electrochemical model is shown in Figure 1, including the negative electrode, separator, positive electrode, and current collectors. The assumptions are made as follows: The electrodes and the separator are regarded as porous media, and impregnated with electrolyte to ensure the directional transfer of lithium ions between the two electrodes; the electrode layer is composed of spherical active particles with uniform sizes and additives, and there is no gas and no side reaction inside.

Based on mass conservation, energy balance, charge conservation, and electrode process dynamics, an electrochemical model is established. In order to simulate the long-term working conditions of the battery pack and reflect most usage of the battery pack, the rate of cycle constant current charge and discharge of the battery are set to 3C. The main electrochemical reaction parameters of the battery are shown in Table 2.

During the electrochemical reaction process at the porous medium electrodes, lithium ions are intercalated or deintercalated between the solid and liquid phases, and the solid compounds undergo an electron exchange reaction at the same time, the porous active electrode remains electrically neutral, and the charge conservation equations are as follows:

\[
- \nabla \cdot i_e = \nabla \cdot i_l = - S_{af} l_{oc} \tag{1}
\]

\[
i_i = - \sigma_s \nabla \phi_i \tag{2}
\]

\[
i_i = - \sigma_s \nabla \phi_i + \frac{2RT \sigma_i}{F} \left(1 + \frac{\partial n_{\text{f}}}{\partial n_{\text{i}}}(1-t_+) \right) \nabla n_{\text{i}} \tag{3}
\]

the boundary conditions are given by

\[
i_s|_{x=1} = i_{\text{app}} \tag{4}
\]

\[
i_s|_{x=3} = i_s|_{x=4} = 0 \tag{5}
\]

\[
\phi_s|_{x=6} = 0 \tag{6}
\]

\[
i_s|_{x=2} = i_s|_{x=5} = 0 \tag{7}
\]

| Parameter          | Cathode | Separator | Anode |
|--------------------|---------|-----------|-------|
| ε_s                | 0.435   | —         | 0.56  |
| ε_l                | 0.28    | 0.4       | 0.3   |
| α_a × α_c          | 0.5     | —         | 0.5   |
| c_l/(mol/m³)       | —       | 1500      | —     |
| c_s/(mol/m³)       | 3900    | —         | 16361 |
| c_s,act/(mol/m³)   | 26390   | —         | 31540 |
| E_a/KJ/mol         | 4       | —         | 4     |
| E_d/KJ/mol         | 20      | —         | 4     |
| σ_s/(S/m)          | 0.01    | —         | 2     |
| k_s/(m².5 mol⁻⁰·⁵ s⁻¹) | 3.626 × 10⁻¹¹ | —       | 1.764 × 10⁻¹¹ |
| ρ_s/(kg/m³)        | 1500    | 492       | 2500  |
| ρ_l/(kg/m³)        | 1200    |           |       |
| C_p/(J kg⁻¹ K⁻¹)   | 1260    | 1978      | 1437  |
| C_p/(J kg⁻¹ K⁻¹)   | 1518    |           |       |
| t_s                | —       | 0.363     | —     |
| T_f/(K)            | 298.15  |           |       |
| F/(C/mol)          | 96487   |           |       |

TABLE 2: Model P(caps) for the battery

Zhang et al.
The electrochemical reaction mainly occurs on the surface of the electrodes, and the local charge transfer current density \( j_{loc} \) is determined by the Butler-Volmer equation given below:

\[
j_{loc} = j_0 \left[ \exp \left( \frac{\alpha_i F \eta}{RT} \right) - \exp \left( - \frac{\alpha_i F \eta}{RT} \right) \right]
\]  
(8)

\[
j_0 = FK_0 C_i^{\alpha_i} (C_{l,max} - C_i)^{\alpha_i} C_i^{\alpha_i}
\]  
(9)

\[
\eta = \phi_1 - \phi_2 - U_e
\]  
(10)

Fick’s 2nd law can be used to describe the diffusion motion of lithium ions in electrode spherical active material particles, and concentrated solution theory can be used for the diffusion and migration of lithium ions in electrolyte solution, the mass conservation equation is as follows:

\[
\frac{\partial c_i}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial r} \left( -r^2 D_s \frac{\partial c_i}{\partial r} \right) = 0
\]  
(11)

\[
\eta \frac{\partial c_i}{\partial t} + \nabla \cdot (- D_i \nabla c_i) = \frac{S j_{loc}}{F} (1 - \tau) \]  
(12)

the boundary conditions are expressed by:

\[-D_i \frac{\partial c_i}{\partial r} \mid_{r=0} = 0
\]  
(13)

\[-D_i \frac{\partial c_i}{\partial r} \mid_{r=r_i} = j_{loc}
\]  
(14)

\[-D_i \nabla c_i \mid_{x=2} = -D_i \nabla c_i \mid_{x=5} = 0
\]  
(15)

In the model, temperature and lithium-ion concentration have an important impact on battery characteristics, so improving the parameters of temperature and lithium-ion concentration correlation can effectively improve the accuracy of the model.

The lithium-ion liquid phase diffusion coefficient \( D_i \) and the ionic conductivity of electrolyte \( \sigma_i \) referred to Ref.32,36 the temperature dependence of reaction rate constant \( k_0 \), and the temperature dependence of the Li\(^+\) diffusion coefficient \( D_s \) in the solid phase follow the Arrhenius formula:

\[
k_0(T) = k_{0,0} \exp \left[ \frac{E_a R}{R} \left( \frac{1}{T} - \frac{1}{T_0} \right) \right]
\]  
(16)

\[
D_s(T) = D_{s,0} \exp \left[ \frac{E_a D}{R} \left( \frac{1}{T} - \frac{1}{T_0} \right) \right]
\]  
(17)

The heat source of battery is calculated by the one-dimensional electrochemical model, and the energy conservation equation in the lithium-ion battery is expressed as:

\[
\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (\nabla (\lambda T)) + Q_{dot}
\]  
(18)

There are three main sources of heat generation during the charging and discharging of lithium-ion batteries: reaction heat \( Q_r \), ohmic heat \( Q_o \), and polarization heat \( Q_p \).

The total heat \( Q_{dot} \) of the battery can be the following expression:

\[
Q_{dot} = Q_r + Q_p + Q_o
\]  
(19)

\[
Q_r = S_{a,loc} \frac{T}{\partial T} = S_{a,loc} \frac{\Delta S}{F}
\]  
(20)

\[
Q_p = S_{a,loc} \eta
\]  
(21)

\[
Q_o = -i_s \cdot \nabla \phi_s - i_t \cdot \nabla \phi_t
\]  
(22)

2.2.2 Theoretical model of fluid heat transfer

The size of the battery pack is 148 × 73 × 140 mm (length × width × height). The distance between the battery pack and cells is 10 mm both top and bottom, which is designed to leave space for sensors layout, circuit connections, and other equipment. The area of inlet and outlet is 73 mm × 10 mm (L × W), the inlet height is 5 mm, and the outlet height is 135 mm, respectively. The battery box is composed of 6 cells, the initial cell spacing is 4 mm, and the battery numbers are 1, 2, 3, 4, 5, and 6 from left to right. Make assumptions for the model: (a) Do not consider the thermal deformation of the heat dissipation system; (b) the heat dissipation system has good thermal insulation performance; (c) ignore the radiation heat exchange during the heating process of the battery; and (d) the battery and the fluid do not produce relative sliding.

The initial conditions are expressed as: the environment temperature is 298.15K, and the initial battery temperature is 298.15 K.

The boundary conditions are as follows: The inlet airflow rate is set to 0.0014 m\(^3\)/s, the outlet is set as the standard atmospheric pressure, and the Reynolds number can be calculated by:

\[
Re = \frac{U_{max} L}{\nu_{air}}
\]  
(23)

where \( L \) refers to the equivalent diameter of the inlet, \( U_{max} \) is the maximum velocity of air in the battery pack, and \( \nu_{air} \) is the kinetic viscosity of the air. The Reynolds number
is greater than the critical value of 2070, which meant turbulence. Therefore, the low Reynolds number $k-\omega$ turbulence model was used, which can improve the accuracy of the model, when the model $k-\epsilon$ is not accurate enough, such as internal flow, separated flow and jet flow et al.

### 2.3 Grid independence study and experimental validation

#### 2.3.1 Grid independence study

High-quality grids are important to ensure the accuracy of simulation results, and the appropriate mesh is divided by the software COMSOL Multiphysics 5.4. The adaptability of the tetrahedrons grid for complex structures is better than that of the hexahedrons grid, and the complexity of heat transfer equations is not great. Therefore, the tetrahedral grid is adopted. Since the 3D geometry of the battery is prismatic with simple structure, the conventional tetrahedral grid is adopted and the normal physics for calibration; while the structure of air domain geometry is relatively complicated, a more refined tetrahedral grid is used, and the hydrodynamics for calibration, which can refine the grid to improve grid resolution in narrow areas. The thicker grid is used in places with little temperature changes and regular structures. Otherwise, the finer grid is used. In general, the minimum grid size is 1 mm and the maximum is no more than 5 mm, which is beneficial to improve the accuracy of the model.

The calculation time will be too long with large number of grids, as can be seen from Figure 2A Independence test of grid number, the differences in the maximum temperature of the battery pack ($T_{\text{max}}$) are not more than 0.02 K when the number of grids is larger than 146 644. The quality of the grid is evaluated by the skewness of the grid, which is a quality measurement tool for most grid types. Compared with an ideal unit, the grid quality will be affected by the too large or too small angle, where the number 1 indicates the best quality. The grid quality distribution under grid number 146 644 is shown in Figure 2B, the grid quality is high, from which the grid number and size can be determined to ensure the simulational accuracy. To ensure the accuracy and save computer resources, the mesh with 146 644 cells is employed.

#### 2.3.2 Experimental validation

To verify the accuracy of the CFD method and the model, as well as the consistency of the temperature distribution of the experimental and simulated, the battery air cooling test platform was built as shown in Figure 3, the commercial type LP2065120 LiFePO$_4$ prismatic battery was experimentally tested, the size of the battery cell is 20 mm $\times$ 65 mm $\times$ 120 mm, the capacity is 12.3 Ah, and the nominal voltage is 3.2 V. The material of anode is graphite, the material of cathode is LiFePO4, and the electrolyte is carbonate based. The systems were wrapped by thermal insulation board of Teflon material of low thermal conductivity to reduce the heat dissipation from the system surface. The bottom structure of the battery pack is shown in Figure 3C, and acrylic plates were used for battery supporting and height determination to ensure that the cells are 10 mm away from the bottom of the battery pack. The inlet airflow velocity of 2m/s meets the requirements, which was controlled by the fan-12038 S7S9 and measured by an anemometer-HT9829. During the constant current charging and discharging, the DC electronic load M9718B and the temperature data acquisition instrument IV3000-32 were used.

![Figure 2](image-url)  
**Figure 2** Results of the grid-dependence and grid quality analysis (A) Independence test of grid number (B) Grid quality distribution
Each single battery was provided with a K-type thermocouple, which was distributed in the middle position below the positive and negative electrode to collect the battery temperature in real time. At the same time, the monitoring point of the corresponding location was set during the simulation to compare simulation and test results. Under the same test conditions, we conducted the same test four times to obtain the average value to ensure the validity of the test and reduce the uncertainty of the test. As shown in Figure 4, the temperature of each cell in the battery pack gradually rises during the experiment, and the cooling performance of structure a’ is better than structure a. In addition, the temperature distribution of structure a is more unbalanced, while structure a’ can obtain better temperature uniformity. As shown in Figure 5, the experimental and simulational results have good consistency, the deviation is no more than 3%, but the experimental results are higher than the simulational results. This is because the model structure is simplified during simulation, ignoring the actual heating of the connecting wires, sensors et al, and the blocking of the airflow path between the cells, resulting in the simulation cooling performance is better than the actual cooling performance. The structure with longitudinal inlet and outlet aligned on different sides. Through the above analysis, the simulation method is validated.

3 | RESULTS AND DISCUSSIONS

In this paper, the four important indicators to evaluate the air cooling performance including the maximum temperature of the battery pack ($T_{max}$), the average temperature of the battery pack ($\bar{T}$), the maximum temperature difference among all cells ($\Delta T$), the standard deviation of the battery pack ($T_{dev}$), where the range of optimal operating temperature is 20-40 °C, the $T_{max}$ should not exceed this range, $\bar{T}$ is expressed as the overall heat of the battery pack, the $\Delta T$ should be limited to 5 °C, and $T_{dev}$ is expressed as the uniformity of battery pack temperature and can be obtained by:

$$T_{dev} = \sqrt{\frac{\sum (T_i - \bar{T})^2}{6}}$$ (24)

where $T_i$ represents the temperature of each cell.

3.1 | Effect of the inlet and outlet relative position

In order to study the influence of the inlet and outlet relative position on the air cooling performance, the 8 schemes in Table 1 are analyzed, the air cooling performance of the battery pack under each scheme is shown in Table 3. When the inlet and outlet distributed on the different sides, the structure
a with longitudinal and aligned inlet and outlet can obtain the better heat dissipation performance compared with the other three structures b, c, and d. $T_{\text{max}}$ and $\bar{T}$ are 307.96 K and 306.38 K, respectively. But the $T_{\text{dev}}$ reaches 0.89 K which is higher than other structures and the temperature uniformity is decreased. Similarly, when the inlet and outlet distribute on the same side, structure a’ achieves better heat dissipation performance than the other structures b’, c’, and d’. $T_{\text{max}}$ and $\bar{T}$
are 307.1 K and 306.13 K, respectively. We can observe that the longitudinal and aligned inlet and outlet can improve the heat dissipation performance.

When the lateral inlet and outlet distribute on the different sides, the structure b with aligned inlet and outlet achieves the lower \( T_{\text{max}} \) and \( T_{\text{dev}} \) compared with the other structures c and d with crossed and diagonal inlet and outlet. Furthermore, the \( T_{\text{dev}} \) of structure b reaches the minimum value of 0.27 K at the expense of increasing the \( T \) to 306.71 K, which indicates that the temperature uniformity is improved. In a similar way, when the inlet and outlet distributed on the same side, the structure b’ achieves the lower \( T_{\text{max}} \), \( T \) and \( T_{\text{dev}} \) than structures c’ and d’. Therefore, the lateral and aligned inlet and outlet can achieve a better uniform temperature of battery pack.

Further, the structure with aligned inlet and outlet (structure a, b, a’, b’) can obtain a better heat dissipation performance or temperature uniformity. The maximum temperature of each cell under different structures is shown in Figure 6. From Table 3 and Figure 6, we can observe that the inlet and outlet on the same side can effectively decrease the \( T_{\text{max}} \) and \( T_{\text{dev}} \). Undoubtedly, the structure a’ obtains the greater improvement, the \( T_{\text{max}} \) decreased by 0.86 K, and the \( T_{\text{dev}} \) decreased by 0.68 K. structure b’ obtains the lowest \( T_{\text{dev}} \) 0.2 K, and temperature uniformity is improved.

In summary, the structure with aligned inlet and outlet on the same side can achieve better air cooling performance. \( T_{\text{max}} \) and \( T_{\text{dev}} \) can be reduced by 2.5% and 76.4% at the maximum, respectively.

### 3.2 Effect of inlet and outlet heights

The results presented in Section 3.1 show that the better heat dissipation performance or temperature is achieved when the inlet and outlet aligned on the same side. Further, the effect of the inlet and outlet heights on the is studied and analyzed to optimize the air cooling performance of the battery pack. It is well known the bottom-in and top-out air cooling method is better. Therefore, the inlet of the battery pack is always located at the bottom half, and the outlet is located in the upper half.

When the longitudinal inlet and outlet aligned on the same side, the comparison of flow field and temperature distribution of battery pack with different inlet and outlet height is shown in Figure 7 the air concentrates to the opposite side of the battery pack away from the inlet and outlet, and the distance is long. It can be seen from Figure 7A and B that when the inlet height remains unchanged and the outlet height reduces to 125 mm, the outlet resistance is increased. Therefore, the air circulation stroke through the cell 1 is increased, and the air circulation stroke through the cells (2, 3, 4, 5) far from the outlet is reduced, the further

**FIGURE 6** The maximum temperature of each cell under different structures with aligned inlet and outlet

**FIGURE 7** Comparison of flow field and temperature distribution under structure a’ with different inlet and outlet height (A) Structure a’, (B) Structure a’-outlet125 with outlet 125 mm, and (c) Structure a’-inlet10 with inlet 10 mm
distance, the higher temperature. As the cell 6 is close to the wall, the cooling performance is not worse. The $T_{\text{max}}$ of each cell is 306.44 K, 306.98 K, 307.03 K, 307.11 K, 307.31 K, and 307.14 K. As the outlet height gradually decreases, the $T_{\text{max}}$ and temperature difference of the battery pack gradually increase, and the air cooling performance is getting worse as shown in Figure 8A. In addition, increasing the inlet height will lead to the greater inlet resistance when the outlet height remains unchanged, which can be seen from Figure 7A and C, the airflow is mainly concentrated at the cell 1, so the temperature of the cells (2, 3, 4, 5) away from the air inlet gradually rises. Due to the cell 6 is close to the wall, the cooling performance is not worse. As the inlet height gradually increases, we can obtain the similar results, the temperature of the battery pack rises more significantly, and the air cooling performance unable to meet requirements as shown in Figure 8B. In summary, the structure a’ can obtain the satisfied air cooling performance only at the lowest inlet height and the highest outlet height.

When the lateral inlet and outlet aligned on the same side, the comparison of the flow field and temperature distribution of battery pack with different inlet and outlet height is shown in Figure 9 that the air concentrates to the opposite side of the battery pack away from the inlet and outlet and the distance is relatively short, so the cells away from the inlet and outlet obtain the better air cooling performance. It can be seen from Figure 9A and B that when the inlet height remains
unchanged and the outlet height decreases to 95 mm, the resistance of outlet and the air circulation stroke in the battery pack are increased, which improves the heat dissipation performance of the cells near the inlet and outlet side, and decreases the $T_{\text{max}}$ and $\Delta T$ to 307.08 K and 3.38 K, respectively. As the outlet height gradually decreases, the temperature of the battery pack generally reduces, especially the two cells near the inlet and outlet (3, 4) as shown in Figure 10A. The $T_{\text{max}}$ of these two cells are reduced by 0.8 K and 0.82 K, respectively. If the outlet height is less than 95 mm, the heat dissipation performance of the cells away from the inlet and outlet (1, 6) becomes worse. The $T_{\text{max}}$ of these two cells is increased by 0.15 K and 0.2 K, respectively. When the outlet height remains unchanged and the inlet height increases to 10 mm, as shown in Figure 9A and C that the resistance of inlet and the airflow near the inlet and outlet side increased, so the heat dissipation performance of the cells close to the inlet and outlet (3, 4) are obvious, and the cells away from the inlet and outlet (1, 6) are not. As shown in Figure 10B, the battery pack obtains the lowest $T_{\text{max}}$ and $\Delta T$ of 307.3 K and 3.49 K, respectively, when the inlet height is 15 mm. If the inlet height continues to increase, the $T_{\text{max}}$ and $\Delta T$ will also gradually increase, resulting in worse temperature uniformity.

In conclusion, initial structure a’ can obtain better air cooling performance when the inlet height is 5 mm and the outlet height is 135 mm. Reducing the outlet height or increasing the inlet height will make the cooling performance worse. Initial structure b’ can obtain better air cooling performance when the inlet height is 5 mm and the outlet height is 95 mm. Compared with increasing the inlet height, reducing the outlet height has more obvious improvement in the air cooling performance.

3.3 | Effect of the cell spacing

Based on the structures a’ and b’-outlet 95 presented above, the temperature distribution of the battery pack is analyzed to optimize the heat dissipation performance by adjusting the cell spacing. The maximum temperature distribution of each cell under the two structures is shown in Figure 11. Obviously, the heat dissipation performance of cells 3 and 4 is better, and cells 2 and 5 are worse, it can be considered that the temperature of the battery pack is distributed symmetrically. Therefore, the nonequidistant symmetrical distribution of cells is used to improve the air cooling performance. As shown in Table 4, the
corresponding widths of the seven flow channels are \( a_0 \), \( a_0 + 2d \), \( a_0 + d \), \( a_0 \), \( a_0 + d \), \( a_0 + 2d \), and \( a_0 \), the expression of the flow channel width is \( 28 = 7a_0 + 6d \), where \( d \) takes 0.5, 1, 1.5, and 2, respectively.

Under nonequidistant symmetrical distribution, the comparison of the structure a’ and b’-outlet 95 air cooling performance is shown in Table 5. When the \( d \) of structure a’ is 0.5 mm, the \( T_{\text{max}} \) and \( \bar{T} \) of the battery pack are reduced to 307.06 K and 306.05 K, respectively, the heat dissipation performance of the battery pack is improved, and the \( \Delta T \) and \( T_{\text{dev}} \) of the battery pack temperature are also decreased, so the temperature uniformity is improved. If the \( d \) keeps increasing, the width of the flow channel 4 will be too narrow, which will lead to the higher temperature of the cells 3 and 4, and the worse heat dissipation performance.

Similarly, when the \( d \) of structure b’-outlet 95 adopts is 1.5 mm, the \( T_{\text{max}} \) and \( \bar{T} \) of the battery pack are reduced to 306.98 K and 305.93 K, respectively, the battery pack has better heat dissipation performance. Furthermore, the \( \Delta T \) is within a suitable range, and the \( T_{\text{dev}} \) is reduced by 22.5%, so the battery pack achieves a more uniform temperature. The results indicate that the structure b’-outlet 95 can obtain better air cooling performance when \( d \) is 1.5 mm.

The comparison of the temperature distribution of the structure b’, b’-outlet 95 and b’-outlet 95-1.5 is shown in Figures 12 and 13. The optimized heat dissipation structure b’-outlet 95-1.5 increases the width of the flow channel near the single cell with worse cooling performance while reducing the width near the single cell with better cooling performance, which is beneficial for dropping the \( T_{\text{max}} \) and \( \Delta T \).

In conclusion, the structure with lateral inlet and outlet aligned on the same side achieves best cooling performance and temperature uniformity when the inlet height is 5 mm, the outlet height is 95 mm and the cell spacing tolerance \( d = 1.5 \) mm.

### 3.4 Future work in terms challenges and chances

In this study, some preliminary enhancements have been obtained in the optimization design of the air cooling system of lithium-ion phosphate battery packs for new energy electric vehicles. However, due to the limitations of time and test equipment, there are still some works can be studied in the future:

1. Considering the time cost, this study simplified the structure of the coupled electrochemical-thermal air cooling model. In the future research, the battery structure model can be appropriately improved to obtain more accurate simulation results.

2. During the use of EVs in winter, low temperature has a greater impact on battery performance. Therefore, not only battery thermal safety issues must be considered, but also the performance improvement of electric vehicles.

| Width of the flow channel [mm] |
|-------------------------------|
| \( d \) | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| 0.5 | 3.57 | 4.57 | 4.07 | 3.57 | 4.07 | 4.57 | 3.57 |
| 1 | 3.14 | 5.14 | 4.14 | 3.14 | 4.14 | 5.14 | 3.14 |
| 1.5 | 2.71 | 5.71 | 4.21 | 2.71 | 4.21 | 5.71 | 2.71 |
| 2 | 2.29 | 6.29 | 4.29 | 2.29 | 4.29 | 6.29 | 2.29 |

**TABLE 5** Air cooling performance of battery pack nonequidistant symmetrical distribution (K)

| Structure | \( T_{\text{max}} \) | \( \bar{T} \) | \( \Delta T \) | \( T_{\text{dev}} \) |
|-----------|----------------|-------------|-------------|----------------|
| a’ | 307.1 | 306.13 | 2.96 | 0.21 |
| 0.5 | 307.06 | 306.05 | 2.92 | 0.23 |
| 1 | 307.15 | 306.03 | 2.93 | 0.28 |
| 1.5 | 307.27 | 306.07 | 3.1 | 0.31 |
| 2 | 307.32 | 306.1 | 3.14 | 0.35 |
during low temperature operation requires more attention and research.

3. As the increasing demand for charging rate, high-current charging will be used to generate more heat. This article focuses on the influence of the air cooling structure of the battery pack. Therefore, the relevant analysis methods can be used to analyze the cooling effect. Other efficient cooling methods such as PCM cooling and liquid cooling should be studied.

4. In this study, the module is composed of 6 lithium-ion batteries, the air cooling performance of the vehicle battery pack and the space utilization of the structure during actual installation are not considered. In future research, the battery pack will be optimized and analyzed according to the use and installation of the vehicle. In addition, the installation and use of more batteries will be further studied.

5. In this study, we considered the effect of the relative position and height of the inlet and outlet, and the distribution and spacing of cells on the air cooling performance. However, other factors require more attention and research, such as the area of inlet and outlet, the shape of inlet and outlet, and the size of battery pack space.

1. Compared with the crossed and diagonal inlet and outlet distributed on the different sides, the aligned inlet and outlet distributing on the same side is helpful to improve the air cooling performance of the battery pack.

2. The inlet and outlet height have a great influence on the airflow resistance, the structure with longitudinal inlet and outlet aligned on the same side can obtain the best air cooling performance only when the distance between inlet and outlet is furthest.

3. For the structure with lateral inlet and outlet aligned on the same side, compared with increasing the inlet height, reducing the outlet height can improve the heat dissipation performance more effectively at an expense of the temperature uniformity.

4. According to the cooling performance of the single cell at different positions, adopting the nonequidistant symmetrical distribution can effectively improve the heat dissipation performance and the uniformity of battery pack temperature.

**Nomenclature**

| Symbol | Description |
|--------|-------------|
| $C_l$  | Electrolyte concentration in the solution phase, mol m$^{-3}$ |
| $C_{s,0}$ | Lithium concentration in electrode particles, mol m$^{-3}$ |
| $C_{s,max}$ | Maximum lithium concentration in the active material, mol m$^{-3}$ |
| $C_p$  | Heat capacity, J kg$^{-1}$ K$^{-1}$ |
| $D_s$  | Diffusion coefficient of lithium in the active material, m$^2$ s$^{-1}$ |
| $D_l$  | Diffusion coefficient of electrolyte, m$^2$ s$^{-1}$ |
| $E$    | Working voltage of the battery, V |
| $E_{aD}$ | Diffusion activation energy, KJ mol$^{-1}$ |
| $E_{ar}$ | Reaction activation energy, KJ mol$^{-1}$ |
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