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A J-Type Air-Cooled Battery Thermal Management System Design and Optimization Based on the Electro-Thermal Coupled Model

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Abstract: Air-cooled battery thermal management system (BTMS) is a widely adopted temperature control strategy for lithium-ion batteries. However, a battery pack with this type of BTMS typically suffers from high temperatures and large temperature differences (ΔT). To address this issue, this study conducted an electro-thermal coupled model to optimize the flow channel structure for reducing the maximum temperature ($T_{\max}$) and ΔT in a battery pack for a “J-type” air-cooled BTMS. The parameters required to predict battery heat generation were obtained from a single battery testing experiment. The flow and heat transfer model in a battery pack that had 24 18650 batteries was established by the Computational Fluid Dynamics software ANSYS Fluent 2020R2. The simulation results were validated by the measurement from the battery testing experiment. Using the proposed model, parameter analysis has been implemented. The flow channel structure was optimized in terms of the duct size, battery spacing, and battery arrangement for the air-cooled BTMS. The original BTMS was optimized to reduce $T_{\max}$ and ΔT by 1.57 K and 0.80 K, respectively. This study may provide a valuable reference for designing air-cooled BTMS.

Keywords: cylindrical lithium-ion battery; electro-thermal coupled; air-cooled battery thermal management system



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1. Introduction

Transportation-related CO₂ emissions are considered one of the uppermost contributors to artificial greenhouse gas emissions. Therefore, an increasing number of countries and regions are actively promoting the gradual substitution of electric vehicles (EVs) for fuel vehicles to achieve the goal of carbon neutrality [1]. Lithium-ion batteries, which offer high energy density and strong power density, are considered the best power source to date and have thus been widely adopted in EVs [2,3]. It is suggested that the temperature of a lithium-ion battery should maintain between 20 °C to 40 °C owing to its intrinsic chemistry and thermal properties [4]. Also, the temperature difference (ΔT) in a battery pack should not be too large; otherwise, it can lead to capacity decay, exacerbating the problem [5]. Thus, a reliable battery thermal management system (BTMS) [6] is crucial for the timely dissipation of heat generated by batteries.

A high-accuracy model to predict heat generation and dissipation accurately is fundamental to designing and optimizing a BTMS. Thus, the model comprises two sub-models: a battery heat generation model and a cooling model for the batteries. The heat generation mechanism by electrochemical reactions during charging and discharging for batteries tended to be complex. Several thermal models were established to predict the relationship between battery heat generation and factors such as the state of charge (SOC) and the battery temperature. These models were primarily divided into two categories: electrochemical-thermal coupled models [7] and electro-thermal coupled models [8]. The electrochemical-thermal model was originally proposed by Kumaresan [9], which related to

the temperature changes in the ion diffusion and electrochemical reaction processes of the battery and was utilized to predict the temperature changes and distribution under various operating conditions. Moreover, it investigated the relationship between the solid–liquid phase concentration diffusion coefficient and ionic conductivity with temperature and ion concentration. Mastali et al. [10] developed a three-dimensional electrochemical model to predict temperature distribution for a square battery and validated the model by comparing the voltage and temperature distribution with experiment data. Li et al. [11] studied the relationship between the total heat generation rate distribution and battery current density using an improved three-dimensional electrochemical-thermal coupled model under the influence of discharge rate and ambient temperature, and it is of great importance for optimizing the design of square battery electrode structures and BTMS. The electrochemical-thermal coupled model approaches the battery from the perspective of electrochemistry to obtain its characteristics. This model tends to be highly complex, involves numerous parameters, and requires significant computational resources. The electro-thermal coupled model is used to investigate the temperature distribution within a battery and provides a macroscopic description of the battery's electrical and thermal properties. Compared with the former coupled model, the electro-thermal coupled model provides lower model complexity, making it a more practical option for real-world applications. Zhang et al. [12] utilized an electro-thermal coupled model to analyze the temperature distribution of thermal runaway during high-rate discharge and short circuit conditions of a 6S4P battery pack. They obtained the three-dimensional temperature distributions for the cold plate cooling channel. Under a discharge rate of 5 C, the maximum temperature ($T_{\max}$) of the battery pack was below 40 °C and the maximum temperature difference ($\Delta T_{\max}$) was below 5 °C. Huang et al. [13] applied a square battery to experimentally verify a combined simulation method of an equivalent circuit model (ECM) and computational fluid dynamics combined with an electro-thermal coupled model under different temperature and charge-discharge rate conditions. The comparison between the simulated and the measured demonstrated excellent agreement. Chen et al. [14] coupled the thermal model with the second-order RC ECM and proposed a battery temperature adaptive estimation method that employed joint Kalman filtering. The method represents the battery's thermal resistance with resistance, the heat source with current, and the thermal capacity with capacitance. Compared with traditional electro-thermal coupled model results, the method has higher temperature estimation accuracy.

Among several cooling methods, liquid cooling and air cooling have been commercialized. Liquid-cooled BTMSs with high efficiency and compactness are usually applied in mid to high-end EVs, whereas an air-cooled BTMS is widely adopted in light-duty EVs owing to its simpler design, high reliability, lightweight and lower cost [15,16]. However, the performance of fast charge and discharge is poor because of the significantly low heat transfer rate and specific heat of air. Those specific manifestations include that (1) the $T_{\max}$ may increase because the air-cooled BTMS may be unable to supply the required cooling load to the battery pack [17]; and (2) a large ΔT within the battery pack is likely to occur. Furthermore, an air-cooled BTMS tends to be with high energy consumption [18]. To address the problems, many efforts to change the flow channel structures and control strategies have been carried out to decrease the ΔT and energy consumption [19]. Kirad et al. [20] investigated the effect of the lateral and longitudinal distances between batteries on temperature and temperature uniformity. Park [21] discovered that using a tapered flow channel in U-type BTMS with the inlet and outlet on the same side can distribute airflow more evenly to every cooling channel, resulting in improved heat dissipation. Xie et al. [22] optimized the inlet angle, outlet angle, and battery spacing of U-type BTMS and achieved reductions of 12.82 % and 29.72 % in the $T_{\max}$ and $\Delta T_{\max}$, respectively. Hai et al. [23] numerically studied a battery pack consisting of 16 cells arranged in various ways in a Z-type airflow channel. Research revealed that aligning the batteries in a pack can effectively reduce the average temperature (T_{av}) of the battery pack, as compared to using a non-aligned arrangement. Liu et al. [24] analyzed the performance of Z-type and U-type air-cooled

BTMS under various battery operating conditions. The results showed that the J-type was more effective than the Z-type and U-type in controlling both temperature rise and pressure drop. By integrating these two structure types and incorporating adjustable valves at the two outlets, the temperature uniformity of the battery pack could be substantially enhanced. Previous research has demonstrated that the cooling efficiency of BTMS was significantly influenced by the flow pattern, which changed according to the inlet and outlet positions. The flow pattern of BTMS changes with the positions of the inlet and outlet, which has a significant impact on the cooling efficiency of the parallel air-cooling BTMS. Considering the different outlet positions, BTMS forms different flow patterns, including Z-type, U-type, and J-type. However, most studies are limited to comparisons of Z-type and U-type structures, with few studies on the influence of changing structural parameters on the cooling performance of cylindrical lithium-ion batteries on the cooling performance of J-type BTMS.

In this paper, the analysis focuses on the impact mechanism of air duct size, spacing between batteries, arrangement of batteries, and air velocity on the performance of the air-cooled BTMS for J-type cylindrical lithium-ion batteries. The rest of the paper is organized as follows. Section 2 constructs a platform for testing the thermal characteristics and develops a battery electro-thermal coupled model. The structural parameters are optimized by simulation in Section 3. Lastly, the relevant conclusions are drawn in Section 4.

2. Model Development

2.1. Computational Fluid Method

Computational Fluid Dynamics (CFD) method is an effective way to calculate the flow field and the temperature field. In ANSYS Fluent, the governing equations were discrete by the finite volume method, including the continuity, momentum, and energy equations. For the cooling air, these equations are expressed as [15]:

Continuity equation:

$$\frac{\partial \rho_a}{\partial t} + \rho_a \nabla \cdot \vec{v} = 0 \quad (1)$$

Momentum equation:

$$\frac{\partial(\rho_a \vec{v})}{\partial t} + \nabla(\rho_a \vec{v} \vec{v}) = -\nabla P_a \quad (2)$$

Energy equation:

$$\frac{\partial(\rho_a C_{pa} T_a)}{\partial t} + \nabla \cdot (\rho_a C_{pa} \vec{v} T_a) = \nabla \cdot (K_a \nabla T_a) \quad (3)$$

The energy governing equation for the battery cell is given by:

$$\rho_b C_{pb} \frac{\partial T}{\partial t} = \nabla \cdot (K_b \nabla T) + q \quad (4)$$

where ρ represents the density, C_p is the specific heat, T is the temperature, P is the pressure, K is the heat conductivity coefficient, and q represents the heat generation rate per unit volume of the battery. To clarify, the subscripts a and b are used to represent the air and battery, respectively.

The heat generation rate is gained by integrating with Ohm's Law [25]:

$$q = \frac{1}{V} \left[I^2 R_e - IT \frac{\partial U_{OCV}}{\partial T} \right] \quad (5)$$

where V , I , R_e , T , U_{OCV} , $\frac{\partial U_{OCV}}{\partial T}$ is the volume of the battery, the current flowing through the battery, and the total internal resistance of the battery, comprising the ohmic resis-

tance and the polarization resistance, temperature, open circuit voltage, and entropy heat coefficient, respectively.

Since the Reynolds number of the air-cooled BTMS typically exceeds 3000 [26], the airflow is turbulent. To account for the effects of turbulence, the widely validated standard k - ε model has been selected for this study. This turbulence model has been shown to be effective in modeling general low-speed and low-pressure flow around obstacles in previous research [27–29]. The k - ε turbulence model includes two equations [3] for the turbulent kinetic energy k and the turbulent kinetic energy dissipation rate ε .

Turbulent kinetic energy equation:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}(\rho k u_j) = \frac{\partial}{\partial x_j}((\mu + \frac{\mu_t}{\alpha_k}) \frac{\partial k}{\partial x_j}) + G_k + G_b - \rho \varepsilon - Y_M + S_k \quad (6)$$

Turbulent kinetic energy dissipation equation:

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_j}(\rho \varepsilon u_j) = \frac{\partial}{\partial x_j}((\mu + \frac{\mu_t}{\alpha_\varepsilon}) \frac{\partial \varepsilon}{\partial x_j}) + C_{1\varepsilon} \frac{\varepsilon}{k} (G_k + C_{3\varepsilon} G_b) - \rho C_{2\varepsilon} \frac{\varepsilon^2}{k} + S_\varepsilon \quad (7)$$

where k is turbulent kinetic energy, ε is turbulent dissipation rate, u_j is the j th component of the velocity vector, and μ and μ_t represent molecular and turbulent dynamic viscosity coefficients, respectively. G_k is the turbulent kinetic energy generation caused by mean velocity gradients, G_b is the turbulent kinetic energy generated by buoyancy effects, Y_M is the fluctuating dilatation contribution in compressible turbulence to the overall dissipation rate, and S_k and S_ε represent source terms of k and ε , respectively, α_k and α_ε represent the inverse effective Prandtl numbers for k and ε , respectively, and $C_{1\varepsilon}$ and $C_{2\varepsilon}$ represent empirical parameters.

2.2. Model and Boundary Conditions Setup

Figure 1a depicts the air-cooled BTMS sketchily. Reference [30] investigated a square-type battery, while this study focused on ICR18650 cylindrical lithium-ion batteries. Cylindrical batteries have been in development for a longer time and are more standardized, which makes it easier to achieve uniform industry standards. Additionally, the manufacturing process for cylindrical batteries is more mature and cost-effective. Considering the battery dimensions and the spatial constraints of the air-cooling system, we designed a parallel arrangement of 24 cells was designed, with 3 cells in series and 8 cells in parallel. Designing a J-type air-cooled BTMS for battery packs, the air is drawn into the system through a lower left inlet and exits through two outlets on the upper left and right sides. The J-type structure is derived from the commonly used U- and Z-type configurations. Its thermal performance is superior to that of the U-type and Z-type, as it features an additional outlet. The J-type BTMS incorporates two outlets that effectively target hot areas, ensuring a narrow range temperature uniformity and significantly enhancing thermal performance. The detailed geometrical parameters of the BTMS are shown in the three-view diagram in Figure 1b. The height of the inlet and outlet ducts is 8 mm, and the distance between the battery pack and the system wall is 5 mm. The external surface distance between adjoining cells is 3 mm. During the simulation process, the thermal-physical field coupling between the air-fluid and the solid battery was defined. The initial conditions for the BTMS were set, including the initial SOC of the battery at 1, the discharge rate, and the physical properties of the battery and air (Table 1 for physical properties of ICR18650 cylindrical lithium-ion batteries and air [31]). The settings for the boundary conditions are shown in Table 2.

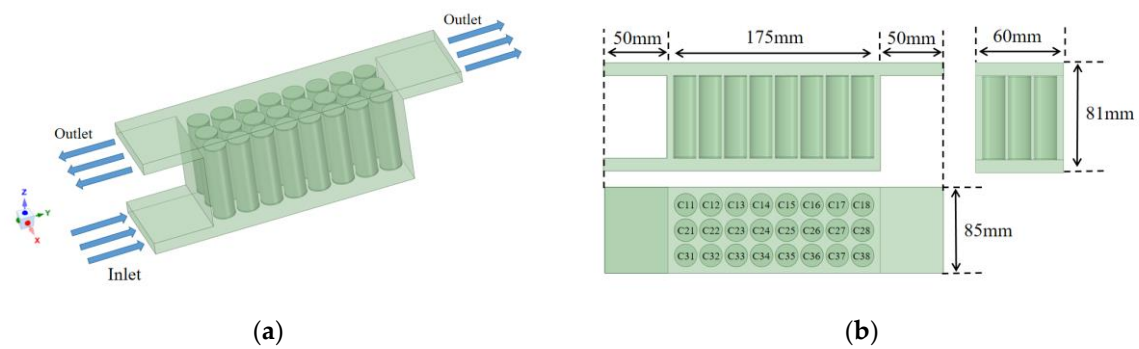


Figure 1. Geometric model of J-type BTMS: (a) 3-D model; (b) Three-view diagram.

Table 1. The properties parameters of air and ICR18650 cylindrical Lithium-ion cell.

	Density ρ (kg/m ³)	Specific Heat Capacity C_p (J/kg/K)	Thermal Conductivity k (W/m/K)	Viscosity Coefficient μ (kg/m/s)
Air	1.225	1006.43	0.0242	1.7894×10^{-5}
Cathode	1347.3	1437.4	1.04	—
Anode	2328.5	1269.2	1.58	—
Cell	2722	1200	Radial thermal conductivity: $k_x = 1.27$ Axial thermal conductivity: $k_z = 27.58$	—

Table 2. Boundary condition settings.

Region	Inlet	Outlet	Top, Side and Bottom	Interfaces between Batteries and Fluid	Initial Temperature	Ambient Temperature
Boundary conditions	Velocity inlet (1–5 m/s)	Pressure Outlet (1.013×10^5 Pa)	Adiabatic non-slip walls	Coupled walls	300 K	300 K

2.3. Experimental Setup and Procedure

To acquire the parameters required for battery heat generation and validate the subsequent results predicted by the model, an experiment was carried out. Figure 2 displays the experimental setup. An ICR18650 lithium-ion battery was applied for the test. Table 3 exhibits the cell specifications. The Battery Tester (CT-4008T-5V6A-S1) setup comprises a mid-range computer, a testing instrument, and a router switch, all interconnected via Ethernet cables to the PC-1. PC-1 provides the charge and discharge instructions for the battery through BTS8.0.0 software, while PC-2 is used for monitoring temperature data. The Temperature Data Collector (34970A) used in this experiment needs to pair with computer software and a K-type thermocouple (SSM1-50) connected via a slot, for the purpose of collecting and recording temperature test data. The experimental system was used in the paper to perform capacity testing and internal resistance testing on cylindrical lithium-ion batteries under different environmental temperatures and different charging and discharging rates.

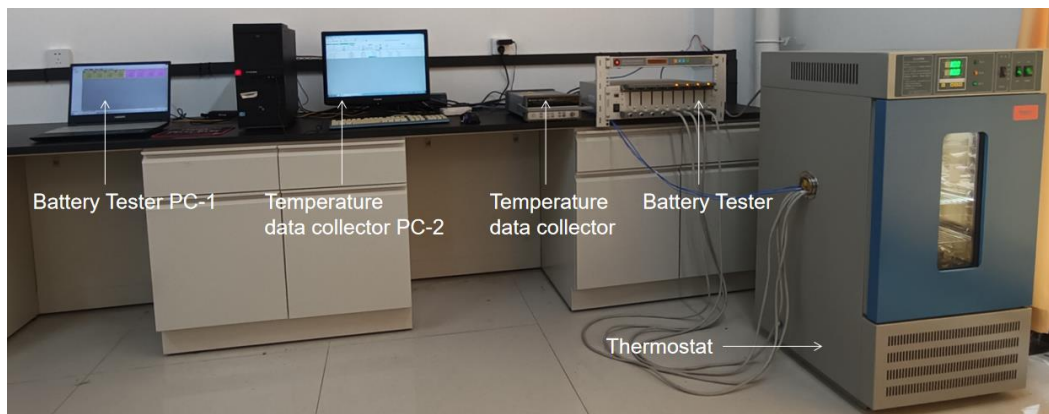


Figure 2. Experimental setup for battery testing.

Table 3. ICR18650 cylindrical cell specifications.

Specifications	Value
Battery brand	Samsung ICR18650
Battery size	Diameter of 18.06 mm, height of 65.02 mm
Charge cut-off voltage	4.3 V
Discharge cut-off voltage	2.6 V
Nominal voltage	3.7 V
Nominal capacity	2 600 mAh
Battery temperature	Charge (283–318 K); discharge (253–333 K)
Anode material	Lithium cobaltate
Cathode material	Graphite

This study employed an electro-thermal coupled model based on the ECM to experimentally and numerically examine the thermal characteristics of lithium-ion batteries. Figure 3 shows the six-parameter model proposed by Chen [32], which consists of a simulation circuit composed of three resistors and two capacitors, where R_s , $R_1 + R_2$ represents the ohmic resistance and the polarization resistance of the battery, respectively.

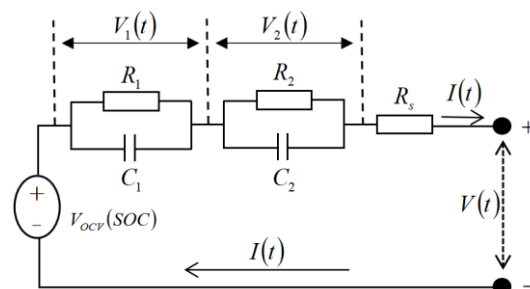


Figure 3. Circuit diagram of second-order RC equivalent circuit model (ECM).

The relationship between voltage and current in the circuit is gained by:

$$V = V_{ocv}(soc) - V_1 - V_2 - R_s(soc)I(T) \quad (8)$$

$$\begin{aligned} \frac{dV_1}{dT} &= -\frac{1}{R_1(soc)C_1(soc)}V_1 - \frac{1}{C_1(soc)}I(T) \\ \frac{dV_2}{dT} &= -\frac{1}{R_2(soc)C_2(soc)}V_2 - \frac{1}{C_2(soc)}I(T) \end{aligned} \quad (9)$$

$$\frac{d(soc)}{dT} = \frac{I(T)}{3600C} \quad (10)$$

where V_{OCV} is open circuit voltage, SOC is the state of charge of a battery, R_s represents the ohmic resistance of the battery, $R_1 + R_2$ represents the polarization resistance of the battery, and C represents the capacity of a battery.

Figure 4 demonstrates that the charge and discharge capacity exhibits the same trend with changes in ambient temperature at different charge and discharge rates. Between the ambient temperatures of 283 K and 313 K, the charge and discharge capacity of the battery increases with the rise in temperature under the same charge and discharge rates. Between the charge and discharge rates of 0.5 C and 2 C, under the same ambient temperature, the charge and discharge capacity of the battery decreases as the charge and discharge rate increases. At an ambient temperature of 313 K and charge and discharge rates of 0.5 C and 1 C, the charge and discharge capacities both exceed the rated capacity, leading to overcharging, which is one of the critical risks for thermal runaway in lithium-ion batteries. It is therefore necessary to perform thermal management of the battery pack under high-temperature conditions. Figure 5 shows that the charge and discharge efficiency increases with temperature. According to the working principle of lithium-ion batteries, the activity of conductive ions in the electrolyte is poor in a low-temperature environment, which affects the battery's charge and discharge efficiency. As the temperature increases, the battery's charge and discharge efficiency improves. A charge and discharge efficiency exceeding 1 indicates the risk of overcharging the battery, also highlighting the importance of the cooling system.

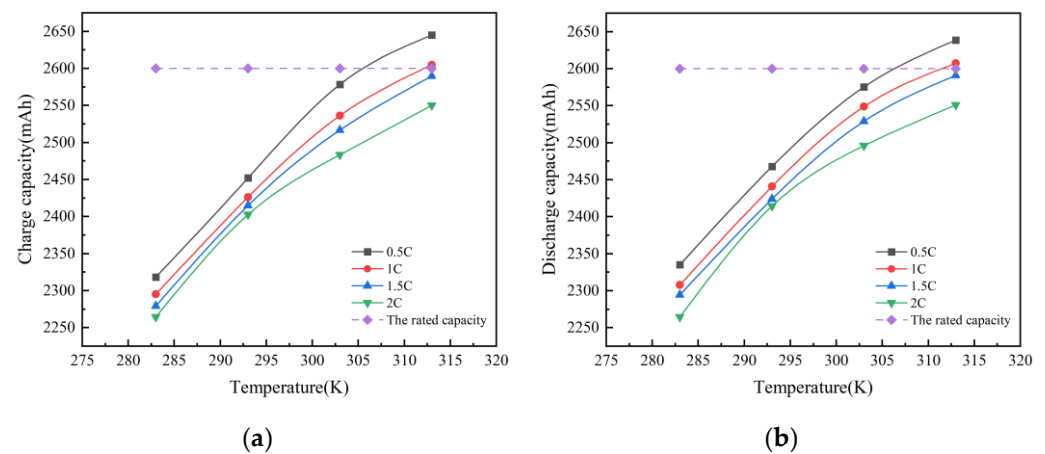


Figure 4. Variations in charge and discharge capacity under the different charge and discharge rates and the ambient temperature: (a) charge capacity; (b) discharge capacity.

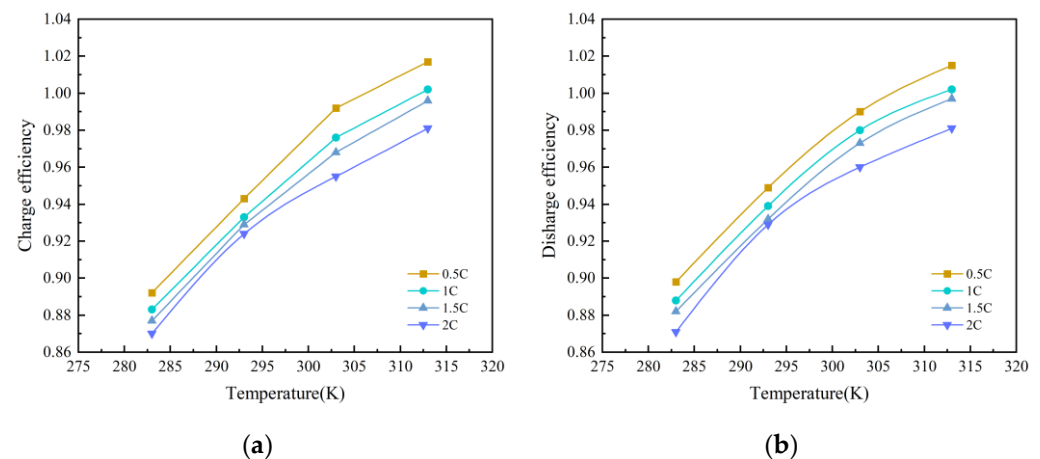


Figure 5. Variations in charge and discharge efficiency under the different charge and discharge rates and the ambient temperature: (a) charge efficiency; (b) discharge efficiency.

The voltage step-change curves of the pulse current at different states of charge were obtained through internal resistance testing experiments under different environmental temperatures and charge–discharge rates [33]. Figure 6a shows a comparison of the pulse voltage step-change curves at the charge–discharge rate of 0.5 C and environmental temperatures of 283 K and 313 K. It can be seen that different environmental temperatures have an impact on pulse charge–discharge, with a larger step-change observed at a lower temperature of 283 K than at a higher temperature of 313 K. The sudden change in voltage since during the measurement of the battery voltage, the voltage drops during constant current discharge, and after a certain period of idle time, the battery voltage returns to a stable state. The stable voltage does not recover to the stable voltage at the previous (SOC). Figure 6b shows a contrast of the pulse discharge voltage step-change at discharge rates of 1 C and 2 C and environmental temperature of 293 K. From the curves presented, it is clear that different discharge rates have an impact on pulse discharge, with a larger step-change observed at a higher discharge rate of 2 C than under a lower discharge rate of 1 C under the same environmental temperature.

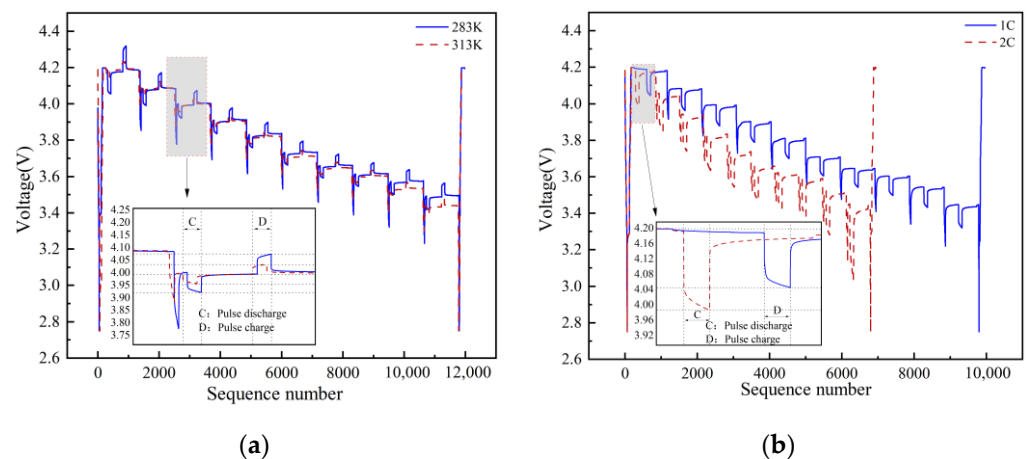


Figure 6. Pulse discharge voltage step-change curves under (a) the charge–discharge rate of 0.5 C and environmental temperatures of 283 K and 313 K; (b) the discharge rates of 1 C and 2 C and environmental temperature of 293 K.

The ohmic resistance R_s and polarization resistance $R_1 + R_2$ under different operating conditions have been calculated by fitting the voltage pulse step change curves obtained from experiments, as shown in Figure 7.

Figure 7 shows a comparison of the difference of the ohmic resistance R_s and polarization resistance $R_1 + R_2$ with SOC under different environmental temperatures. The change of the ohmic resistance R_s with SOC is relatively stable under different charge–discharge rates and different temperatures, with slightly higher values observed at SOC of 0.1 and 1.0. For the same charge–discharge rate, the ohmic resistance R_s decreases with increasing temperature (283 K–313 K), with the highest value observed at 283 K. The polarization resistance $R_1 + R_2$ decreases with increasing temperature. At low temperatures (283 K), the polarization resistance $R_1 + R_2$ is significantly higher at low SOC (0.1–0.2) and high SOC (0.8–1.0). With increasing environmental temperature, the polarization resistance $R_1 + R_2$ decreases significantly at lower and higher SOC, especially at higher SOC. In accordance with the working principle of lithium-ion batteries, the increase in ohmic resistance and polarization resistance is caused by the influence of environmental temperature and charge–discharge rate on the migration speed of lithium ions in the concentrated solution inside the battery.

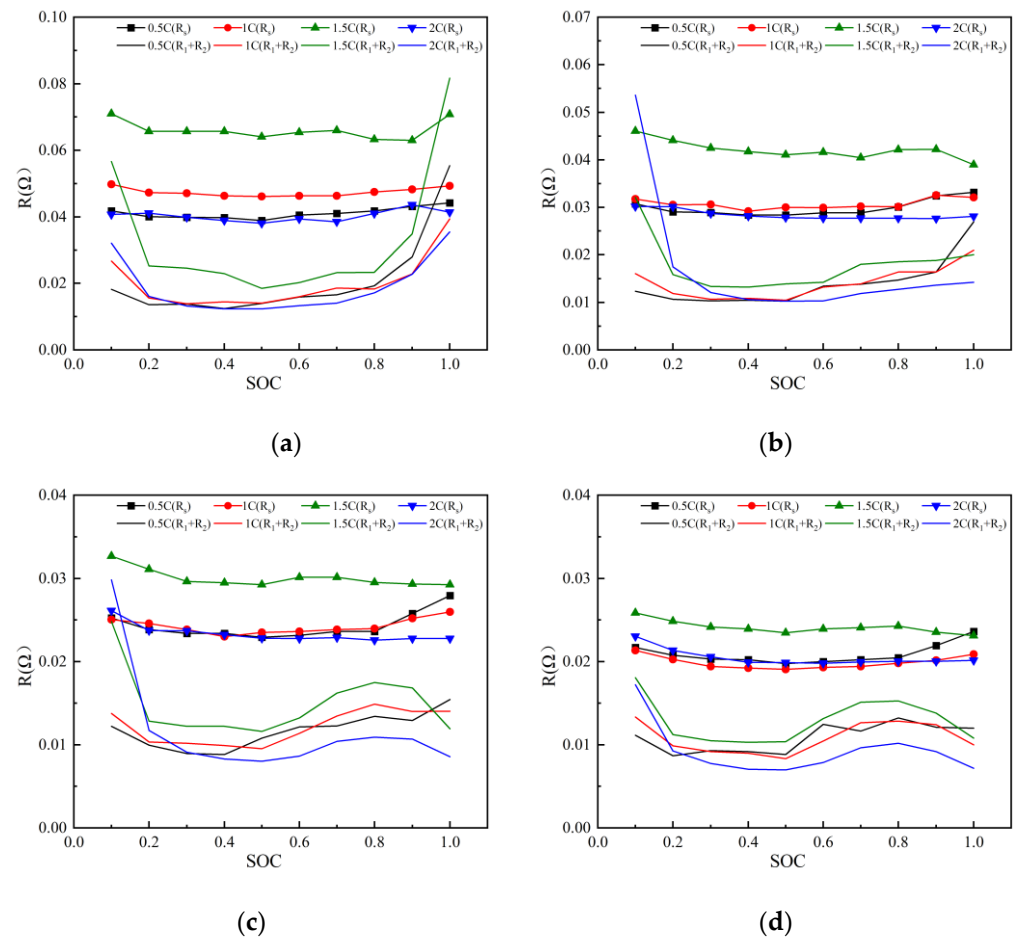


Figure 7. Variations in ohmic resistance R_s and polarization resistance $R_1 + R_2$ with cell SOC under the different charge–discharge rates and the ambient temperature of (a) 283 K, (b) 293 K, (c) 303 K, (d) 313 K.

Within a certain temperature range (283 K–313 K), the ohmic resistance and polarization resistance decrease gradually with increasing temperature. At the same temperature, the ohmic resistance R_s remains almost unchanged as the SOC increases. At lower environmental temperatures, the polarization resistance is higher at lower and higher SOC, and the decreasing trend of the polarization resistance $R_1 + R_2$ at low SOC is less than that at high SOC as the environmental temperature increases. The ohmic resistance and polarization resistance together constitute the total internal resistance of the lithium-ion battery, and their variations determine the different heat generation of the lithium-ion battery under various working conditions.

2.4. Grid Independence Analysis

This paper used structured mesh division of multiple levels of refinement in the BTMS model, and the simulation results began to converge when the grid count exceeded 1.25 million. During the simulation, we monitored the battery's central region and examined how different grid sizes affected the temperature under simulated conditions.

Figure 8 shows the $T_{\max}$ change at different numbers of temperature monitoring points with different grid sizes. Gradual stabilization of the $T_{\max}$ in the simulation occurs as the grid size becomes finer and the number of grids increases, with stabilization being achieved when the number of grids exceeds 1.25 million. Considering the computational resources available for this study, a grid division method with 1,567,850 grids was ultimately chosen for the simulation calculation. Figure 9 presents the result of grid partitioning with a grid

size of 0.1 mm and a total of 1,567,850 body grids. The contact surface between the battery and air has been divided into four boundary layers with a growth rate of $1.4\times$.

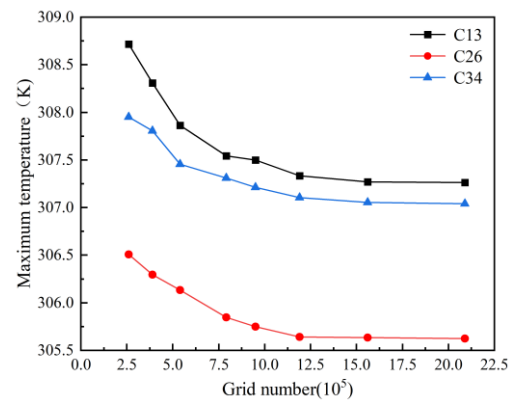


Figure 8. Grid number independence test.

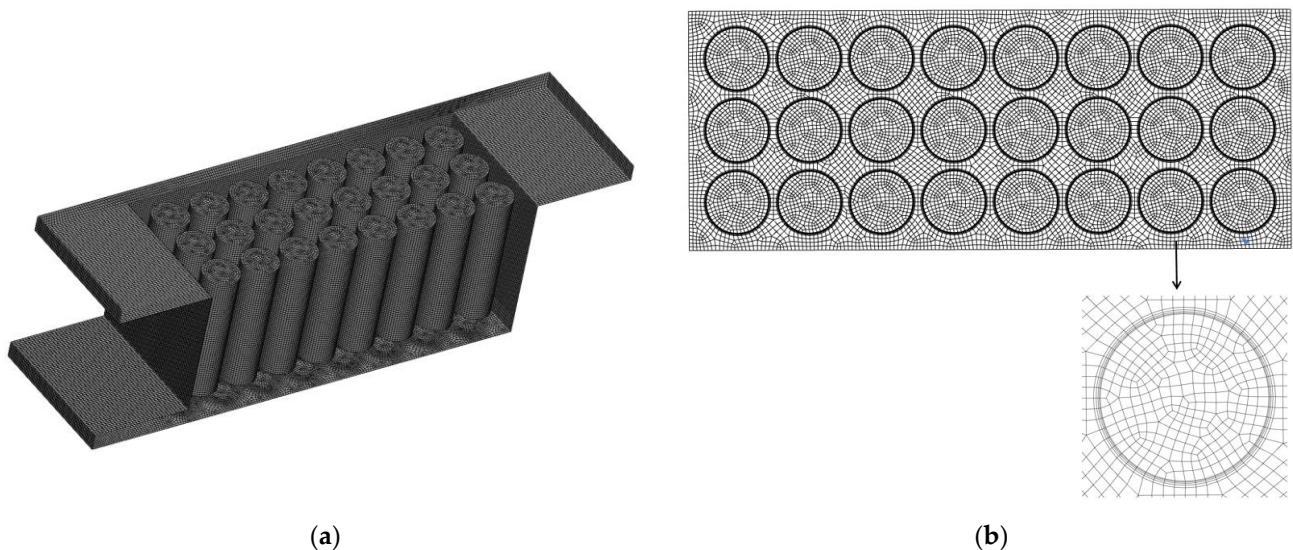


Figure 9. The grid generated on the present geometry: (a) overall grid structure; (b) refined grid at the interface of air and the battery.

2.5. Thermal Model Verification

Finite element simulation was carried out on a single thermal model, and the temperature rise curves obtained from experiments and simulations under different environmental temperatures were compared in Figure 10. At a consistent ambient temperature, an increase in discharge rate is associated with a proportional increase in temperature rise on the battery surface. The temperature rise curves demonstrate similar trends and magnitudes across various discharge rates, indicating the reliability and precision of the ECM utilized in this research to predict temperature changes in lithium-ion batteries.

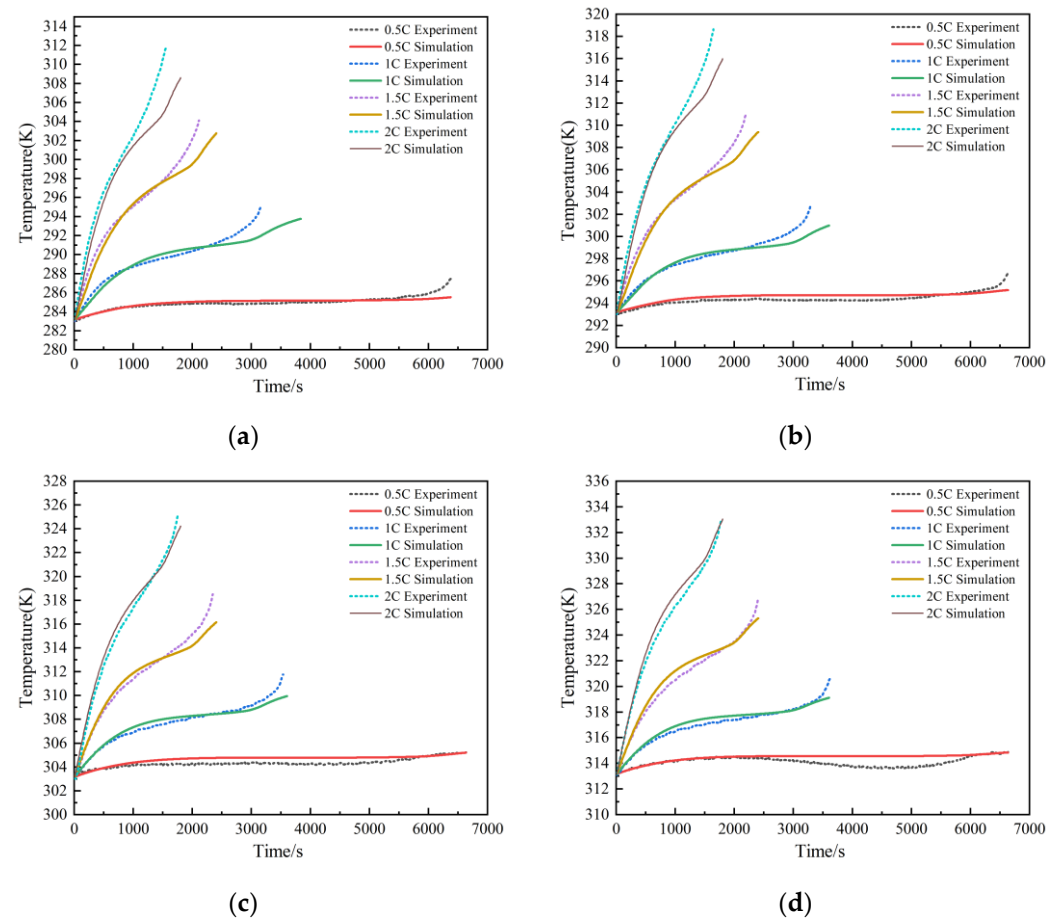


Figure 10. Comparison of experiment and simulation results for different discharge rates under the ambient temperature of (a) 283 K, (b) 293 K, (c) 303 K, (d) 313 K.

3. Simulation Results and Optimization of Air-Cooled BTMS

3.1. Analysis of Simulation Results for Air-Cooled BTMS

Before the simulation process, a fluid–structure coupled heat transfer design was carried out, and the SIMPLE algorithm for solving coupled equations was chosen for the simulation of the lithium-ion battery. The heat generation model was designed using the ECM of the battery module in Fluent 20R2, which was fitted with the polynomial of the internal resistance by HPPC hybrid pulse voltage experimental data. The physical property parameters of the lithium-ion battery were input and set in the Fluent 20R2 software, taking into account the anisotropic thermal conductivity [34]. The radial and axial thermal conductivity coefficients of the battery were set separately, with specific parameters presented in Section 2.2, Table 1. This table encompasses the ICR18650 cylindrical lithium-ion battery and air physical properties.

The reference operating conditions for the battery pack thermal management system were set as follows: ambient temperature of 300 K, incoming air velocity of 2 m/s, and physical parameters of the battery obtained from battery testing experiments. The battery pack was discharged under the 2 C discharge rate, and Figure 11 illustrates the temperature contour map of the J-type BTMS under these reference conditions. It is apparent that during the discharge process, the $T_{\max}$ of all batteries was 307.97 K, and the temperature of the battery remained within the optimal working temperature range. However, an increase in air temperature from the front side towards the rear side leads to the hottest region near the rear side of the module due to a decrease in the local heat transfer coefficient. The batteries above the inlet of the BTMS had less contact with air, and the temperature was higher compared to the batteries near the outlet on the right side. Therefore, this air

cooling system was unable to effectively solve the problem of temperature distribution non-uniformity, and further optimization design was needed.

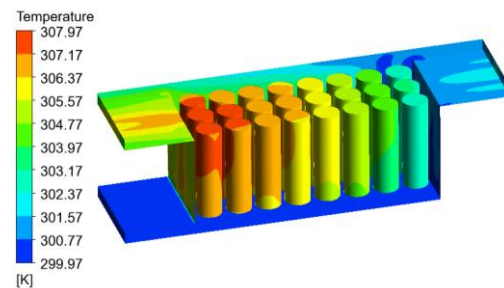


Figure 11. Temperature distribution of the battery pack under the reference operating conditions.

3.2. Optimization of Air Duct Size for Air-Cooled BTMS

In this section, the sizes of the air ducts in the BTMS were studied under reference operating conditions. Given that the width of the air inlet is directly dependent on the width of the battery pack, the optimization of this section was restricted to the height of the air inlet. Four different heights of the air inlet, including 5 mm, 8 mm, 10 mm, and 12 mm, were designed, and the temperature simulation results were studied as illustrated in Figure 12. The operating conditions were an ambient temperature of 300 K, battery discharge rate of 2 C, and incoming air velocity of 2 m/s. For each case, the temperature changes were closely monitored.

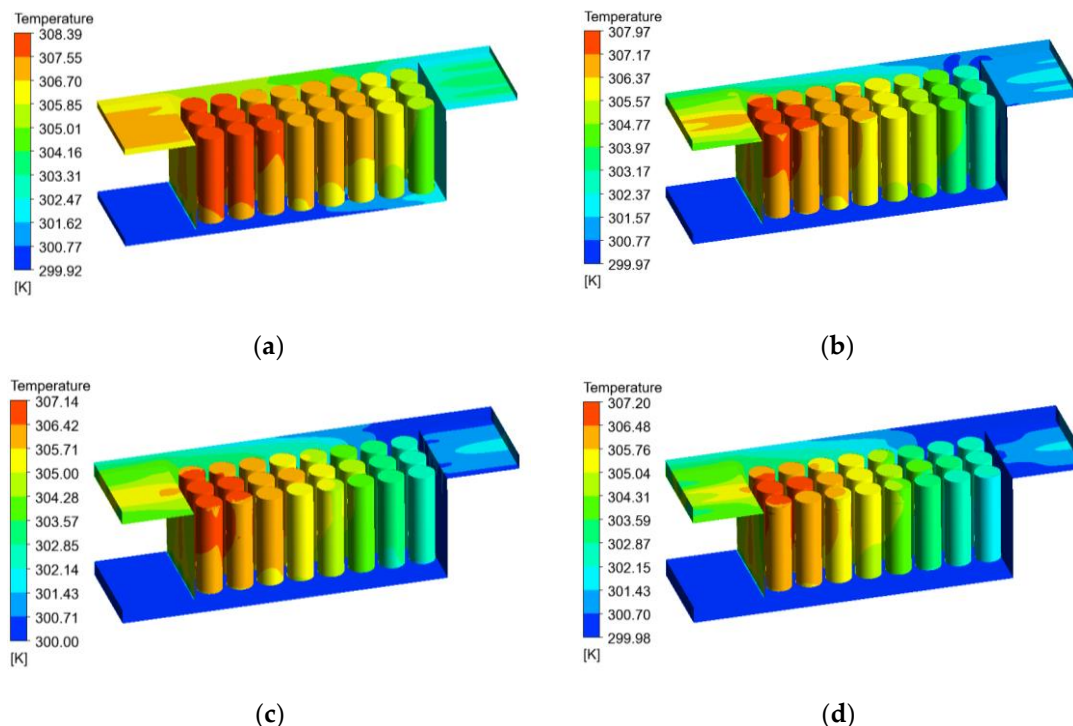


Figure 12. Temperature distribution of the battery pack under different air duct heights: (a) 5 mm, (b) 8 mm, (c) 10 mm, (d) 12 mm.

The simulation results of the temperature contour maps for different air duct heights are shown in Figure 12, which indicates that the change in air duct size affects battery pack temperature. The contrast of the $T_{\max}$ and the minimum temperature ($T_{\min}$) in Figure 13 illustrates that as the height of the air duct increases, the $T_{\max}$ and $T_{\min}$ generally tend to decrease. The increasing height can promote more air into the flow passage and take away more heat. The increase in the height of the air duct will increase the Reynolds

number of the airflow, enhancing the turbulent effect, and thereby improving the efficiency of heat exchange. The $T_{\max}$ is the lowest when the air duct height is 10 mm, and it rises again as the air duct size gradually increases. While the air duct height of 5 mm provides the best temperature uniformity, the smaller channel size may also result in higher flow resistance, resulting in the highest temperature of the battery pack. If the height of the air duct is too small, the cooling airflow may not be able to diffuse sufficiently, potentially creating a thermal gradient within the battery pack. Taking into account both battery pack temperature and temperature uniformity, the optimized air duct height is 10 mm. Optimizing the air duct size can ensure efficient airflow within the battery pack and enhance heat transfer between the surrounding air and the battery pack.

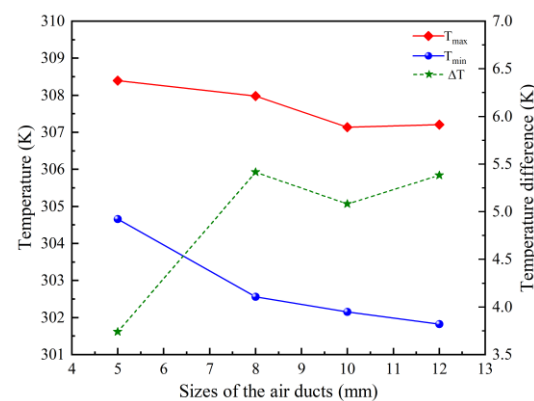


Figure 13. Temperature variation of the battery pack under different air duct heights.

3.3. Optimization of Battery Spacing for Air-Cooled BTMS

In this section, the influence of battery spacing was considered, with spacings of 2 mm, 3 mm, 4 mm, and 5 mm studied in the thermal management simulation as shown in Figure 14. The operating conditions were an ambient temperature of 300 K, battery discharge rate of 2 C, and incoming air velocity of 2 m/s. The temperature changes were monitored for each case.

As shown in Figure 15, the variation in battery spacing did not cause a significant change in the temperature of the battery pack. The $T_{\max}$ observed was 307.23 K at a battery spacing of 2 mm. Gradual increases in battery spacing resulted in minor changes to both the $T_{\max}$ and $T_{\min}$. However, when the battery spacing increased from 3 mm to 5 mm, the ΔT of the battery pack continued to increase, from 4.98 K to 5.05 K, which affected the temperature uniformity. The spacing among the batteries determines the cross-sectional area of individual channels, which dominates the distribution of airflow rate in each flow channel, and, finally, the cooling performance of the module. As the battery spacing increases, the airflow rate between the batteries slows down, absorbing heat from the batteries, and the air temperature increases. The $T_{\min}$ appeared near the outlet of the air duct because the heat is carried out by the air through the right outlet. The temperature uniformity of a battery pack whose battery spacing is too small is worse evidently than that of a battery pack whose battery spacing is large. The reason is that too small battery spacing will affect the development of flow from the laminar boundary layer to the turbulent boundary layer and further deteriorates the heat exchange ability. For this BTMS, the battery spacing of 3 mm is more suitable considering the temperature uniformity.

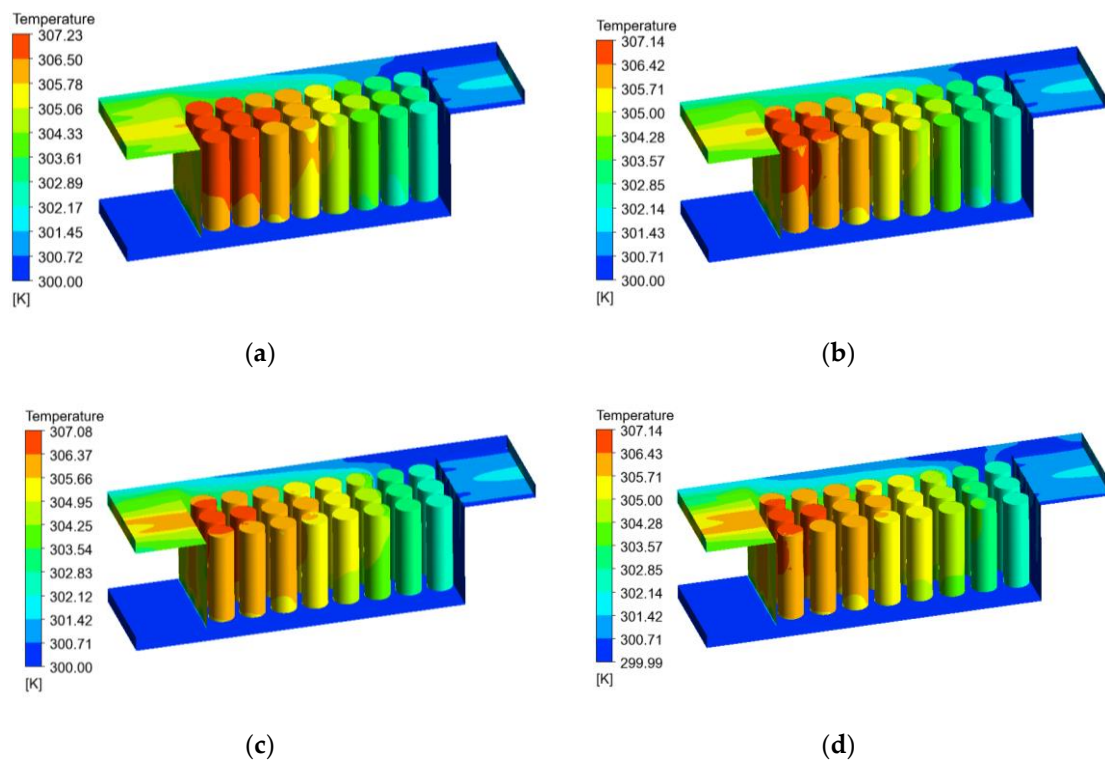


Figure 14. Temperature distribution of the battery pack under battery spacing: (a) 2 mm, (b) 3 mm, (c) 4 mm, (d) 5 mm.

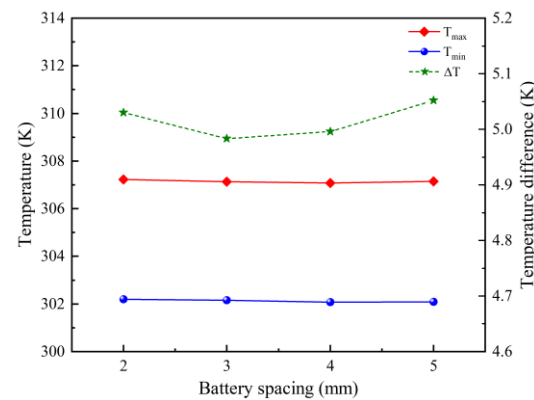


Figure 15. Temperature variation of the battery pack under different battery spacing.

3.4. Optimization of Battery Arrangement for Air-Cooled BTMS

In this section, the battery pack was arranged in a cross pattern, with parallel arrangement in the X and Y directions and staggered arrangement in the Z direction. The purpose of this arrangement was to optimize heat transfer between the battery and the surrounding air, thereby enhancing overall cooling efficiency. In both the X and Y directions, the battery pack was spaced at 3 mm intervals, and the displacement of the battery cross arrangement was 11 mm, which could move the battery to the middle position of the next row of batteries and increase the disturbance of the battery to the airflow. Since the air duct height was set to 10 mm, the staggered displacement of the battery in the Z direction was set to 5 mm, and the battery was moved up and down to the middle position of the air duct.

The arrangement method affects the speed of air flowing over the battery surface and the intensity of turbulence, both of which are crucial in determining the efficiency of convective heat dissipation. Figure 16 illustrates that the battery pack arranged in a cross arrangement in the Z direction exhibits superior temperature uniformity compared to the

cross arrangement in the X and Y directions. As shown in Figure 17, under the operating condition of the 2 C discharge rate and ambient temperature of 300 K, the cross arrangement in the Z direction is optimal for the $T_{\max}$, $T_{\min}$, and ΔT of the battery pack. Compared with the original BTMS, the $T_{\max}$ and ΔT in the cross arrangement in the Z direction have decreased by 1.57 K and 0.8 K, respectively. The battery pack's cross arrangement in the Z direction not only allows for sufficient contact between the air and the battery pack but also changes the flow path of the air, enhancing the local convective heat transfer. In addition, the cross arrangement in the Z direction structure distributed the air more evenly to each cooling channel than the cross arrangement in the X and Y directions and the corresponding airflow directly influenced the cooling effect of the battery.

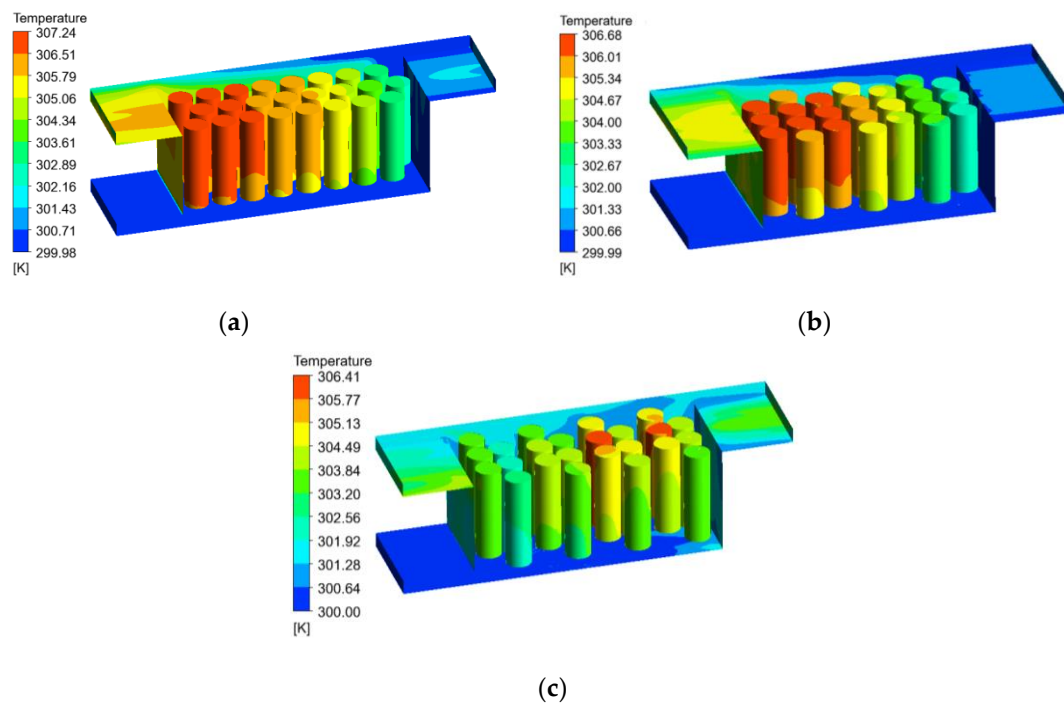


Figure 16. Temperature distribution of the battery pack under different cross-arrangement methods: (a) X direction, (b) Y direction, (c) Z direction.

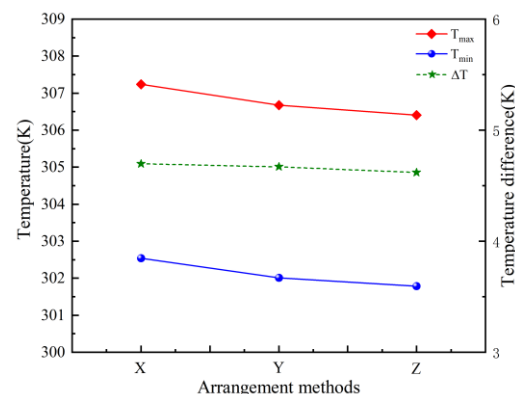


Figure 17. Temperature variation under different arrangement methods.

3.5. Impact of Air Velocity on Air-Cooled BTMS

In the air-cooled BTMS, the system's heat dissipation is directly influenced by the air velocity. Figure 18 presents the velocity distributions on the cross-section at $x = 35$ mm, under different inlet air velocities. The velocity distributions reveal that the high-speed airflow allows more heat to be transferred via convective heat transfer, leading to low-

temperature rise. The high airflow velocity increases the convective heat transfer coefficient between air and batteries. Apparently, the temperature distribution of batteries in BTMS is largely determined by the hydrodynamic and heat transfer characteristics of the airflow. When air enters and passes through different batteries, local vortices appear at the junction of their windward sides, increasing the level of turbulence in the channel. Higher air velocity can improve the efficiency of air heat dissipation, but excessively high air velocity can cause uneven airflow inside the battery pack, thereby affecting the heat dissipation effect and increasing the power loss of BTMS. Therefore, it is necessary to determine the most suitable air velocity range for the air cooling system. Under the benchmark conditions, the effects of different air velocities on the battery pack temperature and air power loss were studied for the optimized BTMS.

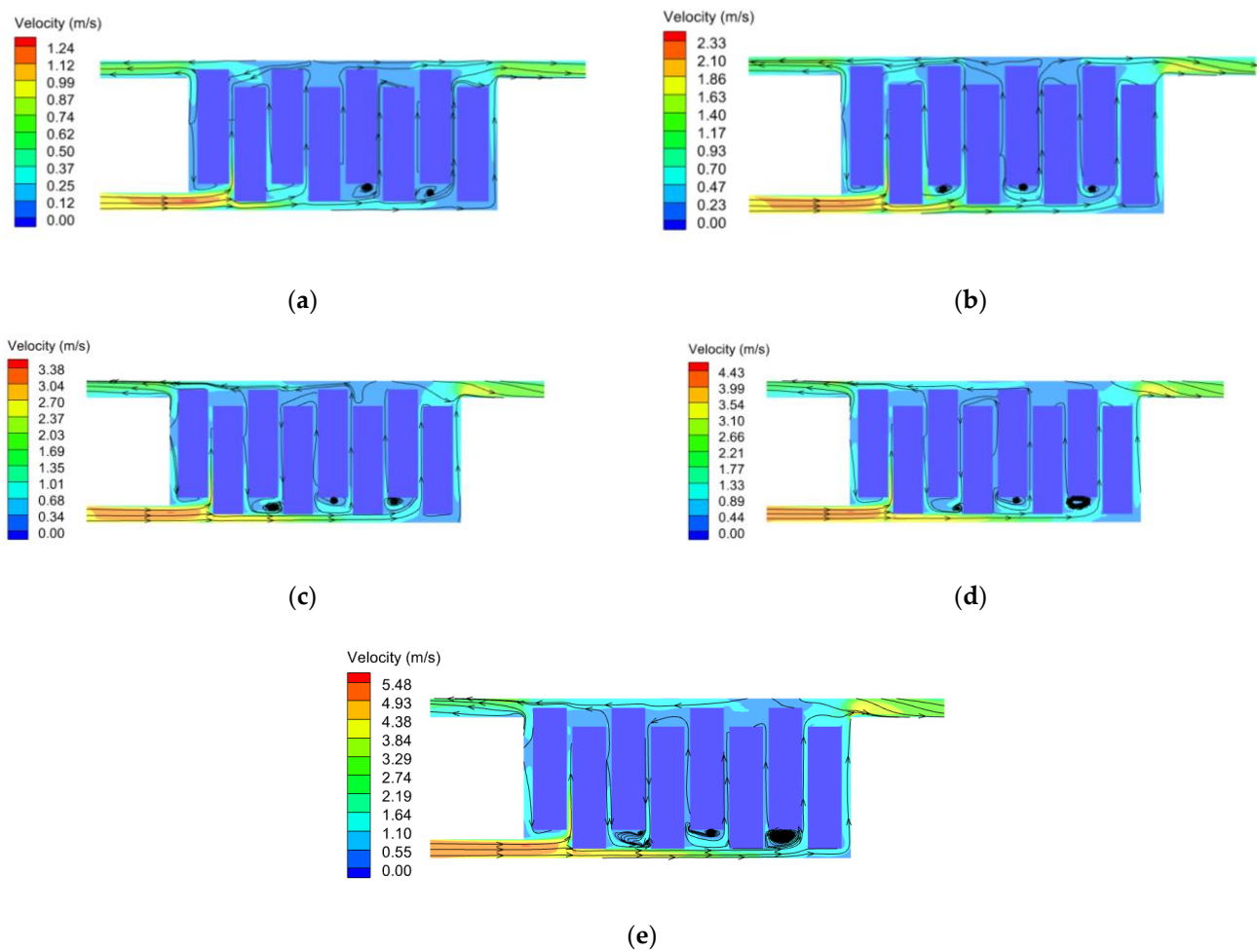


Figure 18. Velocity distribution of different inlet velocities: (a) 1 m/s, (b) 2 m/s, (c) 3 m/s, (d) 4 m/s, (e) 5 m/s.

The cooling power of the air-cooled BTMS can be quantified through the calculation of total pressure differentials at both the inlet and outlet. The air cooling power is calculated using the following formula:

$$m = \rho \times A \times V \quad (11)$$

$$\Delta P = P_1 - (P_2 + P_3)/2 \quad (12)$$

$$G = m \times \Delta P \quad (13)$$

In the formula, m is the mass flow rate of the air, A is the cross-sectional area through which the airflows, V is the velocity of the fluid, ρ is the density of the air, ΔP is the pressure

drop of the air in the system, P_1 is the inlet pressure, P_2 and P_3 are the pressures at the left and right air outlets, and G is the cooling power of the airflow, respectively.

Under the benchmark conditions, assuming that the air is in an ideal gas state, and the cross-sectional area A of the air inlet and outlet for the air cooling system is 0.7 m^2 . Table 4 presents the specific data for the calculation.

Table 4. Calculation results of cooling power under different air velocities.

Air Velocity (m/s)	1	2	3	4	5
Mass flow rate (kg/s)	0.819	1.638	2.457	3.276	4.095
Inlet and outlet pressure difference (Pa)	0.9414	2.3885	4.1943	6.3947	9.0499
Cooling power (W)	1.7124	6.3009	14.4996	27.3439	46.1092

Figure 19a shows the effect of different air velocities on the $T_{\max}$, $T_{\min}$, T_{av} , and ΔT of the battery pack. Increasing the air velocity effectively improves the heat dissipation of BTMS. To achieve optimal cooling performance and temperature uniformity in the battery pack, increasing the air velocity within the range of 1 m/s to 5 m/s is recommended. This has been demonstrated to enhance cooling efficiency. However, the graph shows that the slope of the temperature change gradually decreases, indicating that increasing the air velocity proportionally does not result in a proportional increase in the cooling effect. Figure 19b compares the change of temperature and cooling power by calculating the mass flow rate of the air cooling system, the average pressure drop, and the cooling power of the air cooling system. The graph shows that the increase in cooling power is not proportional to the decrease in battery pack temperature. Increasing air velocity from 1 m/s to 2 m/s results in a 4.589 W improvement in cooling power and a 5.451 K reduction in the $T_{\max}$. When the air velocity is raised from 3 m/s to 4 m/s, the cooling power increases by 12.844 W and the $T_{\max}$ decreases by 0.855 K. In conclusion, while increasing the air velocity can effectively optimize the cooling effect and the temperature uniformity, excessively high air velocity can significantly increase cooling power and lead to poor economic benefits. Taking all factors into consideration, the air velocity of approximately 3 m/s is the optimal setting for the BTMS.

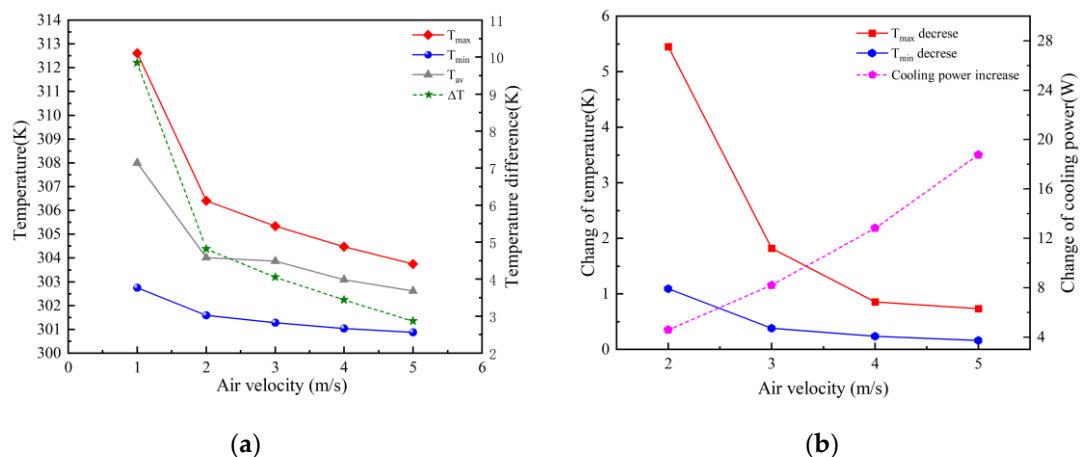


Figure 19. (a) Temperature and temperature difference; (b) change of temperature and cooling power variations under different air velocities.

4. Conclusions

This study constructed a lithium-ion battery thermal characteristic testing platform using experimental research methods and conducted voltage testing, internal resistance testing, and temperature rise experiments on lithium-ion batteries. An electro-thermal

coupled model was conducted to optimize the flow channel structure in the J-type air-cooled BTMS. The main conclusions of this study are as follows:

(1) The internal resistance of the lithium-ion battery under different operating conditions was computed by fitting and calculating the pulse voltage data of the battery obtained through HPPC hybrid pulse power characterization tests. Within the temperature range of 283 K–313 K, both the ohmic resistance and polarization resistance exhibit a gradual decrease with increasing temperature. At lower ambient temperatures, the polarization resistance is larger at both low and high states of charge.

(2) At a consistent ambient temperature, an increase in discharge rate is related to a proportional increase in temperature rise on the battery surface, signifying a corresponding rise in heat generation with an increase in discharge rate. Through the comparison between the temperature simulation and experiment of the lithium-ion battery, the effectiveness and accuracy of the electro-thermal coupled model selected in this study were verified.

(3) A J-type air-cooled BTMS comprising 24 lithium-ion batteries was designed. After optimizing the air cooling system in terms of duct size, battery spacing, and battery arrangement, it was found that the J-type air-cooled BTMS with a duct height of 10 mm, a battery spacing of 3 mm, and a cross arrangement in the Z direction can reduce the $T_{\max}$ and ΔT by 1.57 K and 0.80 K, respectively. The investigation of the optimized air cooling system at various air velocities revealed that the most economically efficient energy consumption air velocity was around 3 m/s, while ensuring that the $T_{\max}$ of the battery pack was within an acceptable range and the temperature uniformity was maintained.

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