Numerical Simulation and Optimal Design of Air Cooling Heat Dissipation of Lithium-ion Battery Energy Storage Cabin

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Abstract. Lithium-ion battery energy storage cabin has been widely used today. Due to the thermal characteristics of lithium-ion batteries, safety accidents like fire and explosion will happen under extreme conditions. Effective thermal management can inhibit the accumulation and spread of battery heat. This paper studies the air cooling heat dissipation of the battery cabin and the influence of guide plate on air cooling. Firstly, a simulation model is established according to the actual battery cabin, which divided into two types: with and without guide plate. Then, at the environment temperature of 25℃, the simulation air cooling experiment of the battery cabin was carried out. The working condition of module was 1C, and the air speed was set to 4m/s. The results show that the average temperature, maximum temperature and temperature difference in the battery cabin reduced by 4.57℃, 4.3℃ and 3.65℃ respectively when guide plate added. The air cooling effect of battery cabin was improved by adding guide plate. There is better consistency between the modules and the modules can operate at more appropriate environment temperature.

Keywords: Lithium-ion battery; battery cabin; battery cooling; guide plate

1. Introduction
In recent years, energy storage has become one of the most concerned issues in the development of China’s electric power industry. Lithium-ion battery has become one of the main battery types for battery energy storage cabin. It has many excellent characteristics such as high energy density, long cycle life and environmental friendliness. At the same time, the thermal characteristics of lithium-ion batteries brings potential safety hazards to the battery cabin.

The safety problem of the battery energy storage cabin has always been the main problem affecting its development. If the battery energy storage cabin is to be developed for a long time, the heat dissipation of the battery cabin becomes the key. On the morning of July 30th, 2021, the energy storage system of Tesla Mega pack in Victoria, Australia exploded. Thirteen tons of lithium-ion batteries in one container were completely ignited, causing serious damage. The battery thermal management system can monitor the safe operation of the battery cabin. However, air cooling is also one of the important measures to improve the safety of the battery cabin.

At present, the research on battery heat dissipation is more focused on the power battery of electric vehicles, and the research on the air cooling of battery cabin is still less. Zehui Liu and Yinghui Gao et al., from The Institute of Electrical Engineering, Chinese Academy of Sciences, took the battery module of electric vehicle as the research object. The influence of changing the structure of air duct on the air cooling of the battery module was studied [1]. Kaijie Yang and Houju Pei et al. from the School...
of Aeronautics and Astronautics of Nanjing University chose the battery module as the research object. The thermal characteristics were analysed and heat transfer characteristics was studied [2]. There are still few researches on the battery cabin, so it is necessary to explore the influence of air cooling on the battery cabin.

The lithium-ion battery will continuously generate heat during the charging and discharging process. Due to the limitation of the battery cabin, the heat generated by the lithium-ion battery will accumulate in the battery cabin and cannot spread to the external environment in time. At the same time, the environment temperature of battery modules in different positions is different, resulting in different temperature rises between battery modules. Long-term use will lead to poor consistency between battery modules, seriously affecting the service life of some battery modules. It will result in an increase in the possibility of heat out of control. However, the current battery management system cannot monitor the temperature of each battery module. So we need to optimize the heat dissipation system of the battery cabin to reduce the temperature rise difference of modules.

Based on this, aiming at the problem of poor heat dissipation ability of battery cabin, change the structure of the battery cabin to make it have better air cooling capacity.

2. Theoretical Basis of Simulation Calculation

The influence of different thermal models on the calculation of temperature field and heat transfer mechanism in the battery cabin were studied. On this basis, the battery cabin model was established and meshed.

2.1. Battery Thermal Model

Through the calculation and analysis of the numerical simulation of the temperature field of the battery cabin, the thermal characteristics of the battery cabin can be effectively analysed. It is of great significance to the design and optimization of battery management system and to improve the safety of battery cabin.

The thermal model of the calculated battery [3] is

\[ \rho C_p \frac{dT}{dt} = k_x \frac{\partial^2 T}{\partial x^2} + k_y \frac{\partial^2 T}{\partial y^2} + k_z \frac{\partial^2 T}{\partial z^2} + q \]  

In which, \( \rho \) is the average density of cell, kg/m\(^3\); \( C_p \) is the specific heat capacity of cell, J/(kg·K); \( T \) is battery temperature, K; \( t \) is time, s; \( k_x, k_y, k_z \) is the thermal conductivity of the battery along the x-axis, y-axis and z-axis, W/(m·K); \( q \) is heat generation rate per unit volume of battery, W/m.

In practical engineering application, there are two main methods: theoretical calculation and experiment to estimate the heat generation rate per unit volume of battery. Among them, the thermal model commonly used in theoretical calculation is Bernardi [4] model.

The estimation formula is

\[ q = \frac{I}{V_b} \left[ (U - U_0) + T \frac{dU_0}{dT} \right] \]  

In which, \( V_b \) is the cell volume, m\(^3\); \( I \) is battery charge and discharge current, A; \( U \) is the cell voltage, V; \( U_0 \) is open circuit voltage for battery, V; \( dU_0/dT \) is the temperature coefficient, given the discharge rate, it is a constant, V/K.

The value of specific heat capacity \( C_p \) of cell can be measured directly by using calorimeter or by theoretical calculation method. That is, the mass weighted average of the specific heat capacity of various materials contained in the cell is carried out, and the calculation formula is

\[ C_p = \frac{1}{m} \sum C_i m_i \]  

In which, \( m \) is the quality of cell; \( m_i \) is the quality of various materials contained in cell; \( C_i \) is the specific heat capacity of various materials contained in cell.
2.2. Cell Heat Transfer Model
Heat transfer process of battery is made up of three parts, which is inside the battery of the heat conduction of each material, fluid thermal convection and thermal radiation three forms on the surface of the battery respectively.

The battery internal conduction of heat energy conservation equation [5] can be expressed as

\[ \rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-k \nabla T) = Q \]  \hspace{1cm} (4)

In which, \( \rho \), \( C_p \), average density and heat capacity for battery; \( T \) for the kelvin temperature, unit for K; \( \nabla T \) is the derivative of temperature with respect to time; \( K \) for the battery to the thermal conductivity, unit for W/(m·K); \( Q \) for battery when the side reaction heat production rate per unit volume, unit for W/m³.

The heat generated by the battery is first conducted inside the battery and then transferred to its surface. Then through the way of thermal convection and radiation to the outside, to achieve heat exchange with the surrounding environment.

The thermal convection between the battery surface and the outside environment can be expressed by Newton's law of cooling [6].

\[ -k \nabla T = -h(T_{ab} - T) \]  \hspace{1cm} (5)

In which, \( h \) and \( T_{ab} \) are natural convective heat transfer coefficient and environment temperature respectively.

2.3. Fluid-structure Coupling Heat Transfer Model
This simulation experiment mainly studies the heat transfer between the battery module surface and the flowing air in the battery cabin. It is necessary to establish a fluid-structure coupling model of the battery module to analyse the heat transfer relationship between the battery module surface and environment.

The expression of fluid-structure coupling heat transfer is

\[ \rho C_p \frac{\partial T}{\partial t} + \rho C_p u \cdot \nabla T + \nabla \cdot q = Q \]  \hspace{1cm} (6)

\[ q = -k \nabla T \]  \hspace{1cm} (7)

3. Establish the Model
By establishing a simulation model similar to the battery cabin, the numerical simulation of the battery cabin can be done to verify the physical experiment.

3.1. Establish the Battery Cabin Model
This paper takes the battery module manufactured by Zhongtian Energy Storage Company as an example to study the thermal characteristics of the battery cabin under different air cooling conditions. The physical picture of the battery cabin is shown in figure 1.

**Figure 1.** The physical picture of the battery cabin.
SolidWorks was used to establish the basic model of the battery cabin. The simulation model was established according to the 1:1 ratio of the actual storage tank, with a length of 12m, a width of 2.4m and a height of 2.8m [7]. A total of 12 groups of battery clusters are placed in the battery cabin, 6 groups on each side, and each group of battery clusters is composed of 15 battery modules.

At the same time, in order to optimize and improve the heat dissipation effect of the battery cabin, a guide plate is added near the inlet of the battery cabin. The width of the guide plate is set to 500mm, which can block the air flow from the inlet and change the air flow field in the battery cabin. The optimized battery cabin model is shown in figure 2.

![Figure 2. The model of lithium-ion battery cabin.](image)

The battery module is composed of 32 batteries in four parallel and eight series. The rated voltage of cell is 3.2V and the rated capacity is 86A·h. The thermal characteristics of lithium-ion battery are shown in table 1.

| The parameter name | Coefficient of thermal conductivity /W·(m·K)^{-1} | Density /kg·m^{-3} | Specific heat capacity /J·(kg·K)^{-1} |
|--------------------|------------------|-------------------|-------------------------------|
| cell (X-axis)      | 3.72              | 2405              | 1329                          |
| cell (y-axis)      | 26                | 2405              | 1329                          |
| cell (z-axis)      | 28                | 2405              | 1329                          |

Module rated voltage 25.6 V, rated capacity 344 A·h, rated power 8.8 KWh. The size of the module is 420mm wide, 600mm deep and 240mm high. The thermal characteristics of lithium-ion battery module are shown in table 2 [8].

| The parameter name                  | Coefficient of thermal conductivity /W·(m·K)^{-1} | Density /kg·m^{-3} | Specific heat capacity /J·(kg·K)^{-1} |
|-------------------------------------|-----------------------------------------------|-------------------|-------------------------------------|
| Module housing (aluminium)          | 238                                           | 2702              | 903                                 |
| cell (X-axis)                       | 3.72                                          | 2405              | 1329                                |
| cell (y-axis)                       | 26                                            | 2405              | 1329                                |
| cell (z-axis)                       | 28                                            | 2405              | 1329                                |

3.2. Mesh Generation

In this paper, meshing program in Ansys Workbench 2020 software is used to conduct mesh division. The module surface and fluid domain are meshed by different methods. The meshing results of the battery cabin are shown in figure 3.
4. Simulating Calculation

By establishing and physical simulation model, the same simulation conditions in real environment, can realize the purpose of the simulation. Analyse the results obtained, and then optimize the method.

4.1. Simulation Analysis of Battery cabin Model

According to the data of module size and heat dissipation, the cooling area of battery is 178.85 m². The fluid-structure coupling field is used to solve the heat flow field in the battery cabin, the convective heat transfer condition can be used directly in flow field [9].

Inlet and outlet boundary conditions include temperature, air velocity and air pressure. The inlet is set as velocity-inlet, the inlet wind speed is 4m/s, and the inlet temperature is set to 25 °C consistent with the environment. The outlet is set to pressure-outlet, and the outlet pressure is set to ambient pressure and to inhibit reflux. The heat dissipation rate of the battery module is 13757.2 W/m³ when working condition is charging at 1C. The surface wall of the battery module is set as heat, and the other surface is set as wall.

This topic chooses a relatively simple pressure-based solver to simulate and solve the model. The velocity formula chooses absolute velocity, and the time setting chooses transient study. After the convergence of Fluent calculation results, the temperature cloud diagram of the heat dissipation surface of the battery cabin model can be obtained, as shown in figure 4.

It can be seen from the figure that the temperature distribution in the battery cabin is very uneven. The average temperature in the battery cabin is 53.98°C, and the high and low temperature is 43.15°C. The temperature is highest in the center of the battery cabin, reaching 70.65°C. The closer it is to the edge of the battery cabin, the lower the temperature is. The lowest temperature was 27.5°C at the top of the battery cabin and near the inlet. This is due to the formation of vortices in the battery cabin as...
air enters and exits from the inlet. The flow field at the edge of the battery cabin has a faster speed and can conduct better heat exchange with the battery module. The flow field at the center of the battery cabin has a weak effect and cannot form a good heat exchange with the battery module. This view can also be verified by combining the flow field diagram, as shown in figure 5.

Figure 5. Flow field diagram of battery cabin.

Through the flow field diagram, the upper part of the air flow velocity is large, at 3.2m/s. Most of the air through outlet went straight out of the cabin, only a small portion of the air of the lower half form a circle. The air flow rate in the central part of the cabin is 0.8m/s. A lot of air is not fully heat exchange with the battery module, the battery cabin can't get good heat dissipation effect.

4.2. Simulation Analysis of Optimized Battery Cabin Model

In order to make the battery cabin get better heat dissipation capacity, the heat exchange intensity between the battery module and the air can be enhanced. The flow field can be regulated by the guide plate to achieve the purpose of uniform flow field. So that the air and the battery module can be more fully contacted.

Generally, the inlet and outlet are placed at the upper position near the top, so the air flow will only form convection in the upper part of the battery cabin. It is difficult to exchange air in the lower part of the battery cabin. The heat dissipation effect of the module located in the lower part of the battery cabin is not ideal. A guide plate is installed on the top of the battery cabin to prevent air from flowing directly out of the air outlet, change the flow direction of air. It makes the air flow in the whole battery cabin, so that the battery module can have a better heat dissipation effect.

The temperature cloud diagram of the heat dissipation surface of the optimized battery cabin model is shown in figure 6.

Figure 6. Heat dissipation cloud of optimized battery cabin.
As can be seen from the figure, when the guide plate is added, the temperature distribution in the battery cabin is more uniform [10]. And the high and low temperature and average temperature of the battery heat dissipation surface both decrease. The average temperature in the battery cabin is 49.41℃, and the high and low temperature is 39.5℃. The highest temperature was found only in a small area at the back of the battery cabin, at 66.35 °C. The lowest temperature was 26.85℃ in the area around the inlet and guide plate. This is because when the air enters, the flow is blocked by the guide plate, which artificially changes the flow direction of the air. So that it has to flow to the lower part of the battery cabin and have a more adequate heat exchange with the battery module. This view can also be verified by combining with the flow field diagram, as shown in figure 7.

![Flow field diagram of optimized battery cabin.](image)

It can be seen from the figure that the air is blocked by the guide plate when entering the battery cabin and its flow direction changes downward. At this time, the air flows through the battery module at a faster speed, 2.8m/s and can conduct a more adequate heat exchange with the battery module. The air is mainly circulated in the rear part of the battery cabin, and part of the air is circulated in the front part of the battery cabin. So that the flow field in the battery cabin is more complicated, and all the battery modules can fully contact with the air to achieve better heat dissipation effect.

5. Conclusion

In this paper, a lithium-ion battery storage cabin is taken as the research object, and its air cooling heat dissipation is analysed and optimized based on SolidWorks and Ansys software. Draw the following conclusions.

1) Air cooling system can be added to the battery cabin to cool the battery module in the battery cabin. However, due to the structure of the battery cabin, the air can only form a simple circulation in the battery cabin. As a result, the battery module cannot get uniform heat dissipation. The battery module in the central area of the battery cabin will generate a higher temperature rise. The maximum temperature in the central area is 70.65℃. After a long period of operation, the battery module in the central area will shorten the service life, and the consistency between the battery modules will be worse.

2) After the addition of the guide plate in the battery cabin, the flow field in the battery cabin becomes more complicated. Multiple cycles are formed in the battery cabin, and more contact with the battery module can be obtained. The maximum temperature in the battery cabin is reduced by 4.3℃ and the maximum temperature occurs in a smaller area. The average temperature in the battery cabin reduced by 4.57℃ and the temperature difference between high and low reduced by 3.65℃.

So that more heat exchange can be carried out and the air cooling of the battery modules is better. The temperature rise between the battery modules is more even, and the consistency between the battery modules is better.
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References
[1] Liu Z H, Gao Y H, Sun Y H and Yan P 2021 Research progress in heat dissipation technology of Li-ion battery Battery Bimonthly: 310-314.
[2] Yang K J, Pei H J, Zhu X L, Zou Y T, Wang J Y and Shi H 2020 Research and optimization of thermal design of a container energy storage battery pack Energy Storage Science and Technology:1858-1863.
[3] Yang K, Li D H, Chen S and Wu F 2008 Thermal model of batteries for electrical vehicles Transactions of Beijing Institute of Technology: 782-785
[4] Pan H H, Li Y J, Zhang M, Liang G and Chen L 2021 Multiple factors dynamic heat generation rate model of lithium-ion battery Automotive Engineering: 204-209.
[5] Xu M, Zhang Zh Q, Wang X, Jia L, Yang L X 2014 Two-dimensional electrochemical–thermal coupled modeling of cylindrical LiFePO4 batteries Journal of Power Sources: 256.
[6] Yuan P 2020 The concept and application of "Thermal Resistance" in heat transfer courses Electronics World: 53-54.
[7] Niu Zh Y, Wang H R, Jin Y, Sun L, Tao F B and Yin K Y 2021 Overcharging and runaway characteristics of lithium-ion phosphate battery modules at different rates Electric Power Engineering Technology: 167-174.
[8] Wang H R, Sun Y T and Jin Y 2021 Simulation study on overcharge thermal runaway propagation of lithium-iron-phosphate energy storage battery clusters Journal of Mechanical Engineering: 32-39.
[9] Feng J Y, Dai Z Q, Zhang J P and Zhang T Zh 2013 Research on the temperature field characteristics of LiFePO4 power battery based on ansys workbench 12.0 Journal of Qingdao University(Engineering & Technology Edition): 51-55+64.
[10] Hu R H 2014 Numerical Simulation on the Thermal Property and Thermal Management of the Lithium-ion Battery for Electric Vehicle South China University of Technology.