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Thermal Simulation Study of Liquid Cooling System for Energy Storage Battery Pack

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Abstract: To address the heat dissipation requirements of large-capacity energy storage battery packs, this paper takes a 587 Ah 1P104S energy storage battery pack as the research object and conducts thermal simulation analysis of a liquid cooling system. A three-dimensional thermal simulation model including cells, liquid cold plate, and thermal interface materials is established, and numerical simulation is performed under specified flow rate and inlet temperature conditions. Through analysis of the simulation results, the flow resistance characteristics and temperature uniformity performance of the current liquid cooling scheme are evaluated. Existing problems are identified, and targeted improvement directions are proposed from three aspects: flow channel topology optimization, flow distribution improvement, and heat exchange layout adjustment, providing a basis for subsequent structural optimization.
Keywords: energy storage battery pack; liquid cold plate; thermal simulation; temperature uniformity

1.INTRODUCTION

With the development of the energy storage industry toward large capacity and high energy density, cells above 500 Ah are gradually becoming mainstream. The increased heat generation caused by higher cell capacity imposes greater demands on thermal management systems. Liquid cooling technology, with its advantages of high heat exchange efficiency and compact structure, has become the preferred cooling solution for large-capacity energy storage systems. As the core component of the liquid cooling system, the flow channel structure of the liquid cold plate directly determines the heat dissipation performance and flow resistance, making it a key aspect of thermal management design.

Currently, common liquid cold plate flow channel configurations each have their own advantages and disadvantages. How to balance heat exchange efficiency and temperature uniformity within a limited space is a challenge in engineering design. This paper takes a 587 Ah 1P104S energy storage battery pack as the object, evaluates the heat dissipation performance of a liquid cooling flow channel scheme through modeling and simulation, analyzes existing problems, and proposes improvement ideas.

2 MODEL AND METHODS

2.1 Mathematical Model

2.1.1 Battery Heat Generation Model

The Bernardi battery heat generation model is adopted, treating the cell as a uniform internal heat source with volumetric heat generation rate:

$$q_V = I[(E_0 - U) - (dE_0/dT_b)T_b]/V_b \qquad (1)$$

2.1.2 Flow and Heat Conduction Equations

Coolant flow follows the conservation equations of mass, momentum, and energy:

Mass conservation equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0 \qquad (2)$$

Momentum conservation equation:

$$\frac{\partial u}{\partial t} + \nabla \cdot (u \otimes u) - \nabla \cdot \left(\left(\frac{\mu + \mu_t}{\rho} \right) \nabla u \right) = S_i - \frac{1}{\rho} \nabla p \qquad (3)$$

Energy conservation equation:

$$\frac{\partial (\rho T)}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i T) = \frac{\partial}{\partial x_i}\left(\frac{k}{c_p} \cdot \frac{\partial T}{\partial x_i} \right) + \frac{S_T}{c_p} \qquad (4)$$

Battery heat conduction differential equation:

The battery heat conduction is treated as three-dimensional transient heat conduction with constant physical properties and internal heat generation, governed by:

$$\rho_b C_p \frac{\partial T_b}{\partial t} = \frac{\partial}{\partial x}\left(\lambda_{bx} \frac{\partial T_b}{\partial x} \right) + \frac{\partial}{\partial y}\left(\lambda_{by} \frac{\partial T_b}{\partial y} \right) + \frac{\partial}{\partial z}\left(\lambda_{bz} \frac{\partial T_b}{\partial z} \right) + q_V \qquad (5)$$

where: rho is fluid density; u is fluid velocity; mu is dynamic viscosity; mu_t is turbulent viscosity; S_i is the momentum source term; p is pressure; C_p is fluid specific heat capacity; T is temperature; u_i is the thermal energy increment in the x_i coordinate direction; k is heat transfer coefficient; lambda_b is the anisotropic thermal conductivity of the battery, W/(m·K); rho_b is battery density, kg/m³; t is time, s.

2.2 Physical Model and Computational Domain

2.2.1 Geometric Model

The research object is a 587 Ah 1P104S energy storage liquid-cooled battery pack, consisting of 104 cells connected in series, with a bottom liquid cooling scheme. The main components of the battery pack include cell modules, liquid cold plate, thermal pads, insulation pads between cells, module beams, end plates,

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and insulation boards. The liquid cold plate is located at the bottom of the cell modules and contacts the cell bottoms through thermal pads for heat transfer. Insulation pads are placed between cells to suppress lateral heat conduction.

To improve computational efficiency, reasonable simplifications are made to the model. Structures that have minimal influence on heat transfer, such as bolts and wire harnesses, are neglected, while core thermal path components including cells and the liquid cold plate are retained.The simplified simulation model is shown in Figure 1.

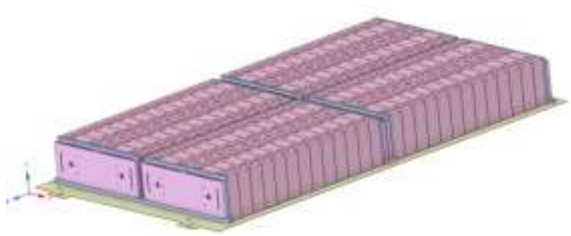

Figure 1 Simplified simulation geometric model

2.2.2 Liquid Cold Plate Flow Channel Structure

The liquid cold plate studied in this paper adopts a conventional liquid cooling flow channel layout. Coolant enters the flow channel region from the inlet header, passes through the internal channels for heat exchange, and exits from the outlet header. The flow channel cross-section remains consistent along the path, and the overall structure is suitable for mass production using stamping and brazing processes.

2.3 Mesh Generation and Boundary Conditions

Tetrahedral unstructured meshes are employed, with refinement in the flow channels and key heat exchange regions. The total mesh count is approximately 26 million, with a minimum mesh size of 1 mm and a maximum skewness of 0.77 (as shown in Figure 2).

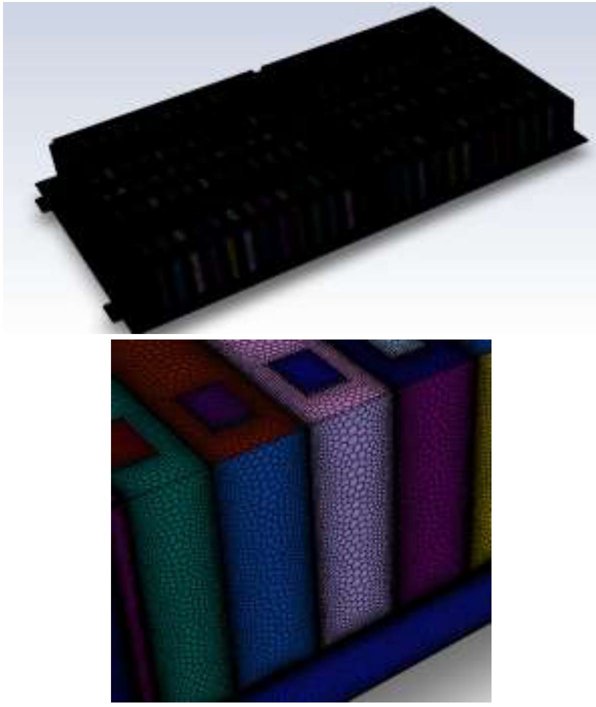

Figure 2 Simulation mesh of the energy storage liquid-cooled battery pack

The boundary conditions are set as follows: the inlet of the liquid cold plate is set as a velocity boundary with specified total flow rate and inlet temperature; the outlet is set as a pressure boundary with gauge pressure of 0 Pa. A volumetric heat source is applied to the cells, with a single cell heat generation power of 28.2 W. The ambient temperature is 25°C, and the natural convection heat transfer coefficient on the outer surface of the battery pack is taken as 5 W/(m²·K). Solid-solid interfaces are set as coupled thermal conduction boundaries.

3 RESULTS AND DISCUSSION

To systematically evaluate the hydraulic characteristics and heat dissipation performance of the liquid cold plate, numerical result analysis is conducted from three aspects: flow resistance characteristics, cell temperature field, and cold plate temperature field, based on the three-dimensional thermal simulation model and rated operating conditions. The performance and existing problems of the current scheme are identified.

3.1 Flow Resistance Characteristics Analysis

Flow resistance is a core hydraulic performance indicator of the liquid cold plate, directly determining the power consumption and operational economy of the system pump. Under the rated flow rate, the simulation obtains a total pressure difference of 41.082 kPa between the inlet and outlet of the liquid cold plate. From the experimental data, the pressure gradually decreases along the flow direction, with obvious local pressure mutations at flow channel turns, which are concentrated areas of local resistance loss.

From the perspective of resistance composition, the overall flow resistance is relatively high, exceeding the reasonable range of 30 kPa typically expected for energy storage liquid cold plates. This is mainly due to the combined effects of flow channel length, cross-sectional dimensions, and turning structures. Excessive flow resistance will directly increase the required pump power and operational energy consumption, which is detrimental to the overall system economy.

3.2 Cell Temperature Field Analysis

The operating temperature level and temperature uniformity of cells are core evaluation indicators of battery thermal management systems, directly affecting the cycle life, capacity utilization, and operational safety of cells.

3.2.1 Cell Top Surface Temperature Distribution

From the cell top surface temperature contour map, it can be observed that the overall maximum temperature of the battery pack is 40.1°C, with high-temperature regions concentrated in the middle of the battery pack. The temperature distribution generally exhibits a "high in the middle, low at the edges" pattern: the middle cells have longer heat dissipation paths and tend to accumulate heat, resulting in the highest temperatures; the cells at both ends benefit from auxiliary heat dissipation through the end plates and enclosure via natural convection with the environment, resulting in relatively lower temperatures.

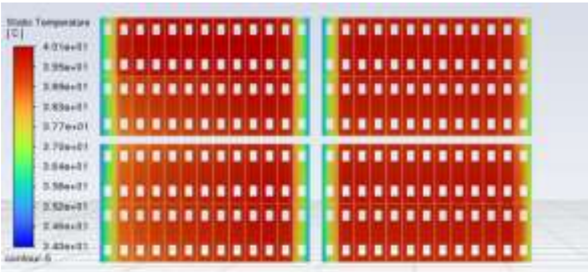

Figure 3 Temperature contour map of cell top surface

The statistical results show that the maximum temperature difference on the cell top surface reaches 6.1°C, indicating poor temperature uniformity that exceeds the typical design requirement of 3°C. Along the coolant flow direction, the cell regions corresponding to the flow channel inlet side have lower temperatures, while the outlet side regions have higher temperatures. The gradual temperature rise of the coolant along the flow path leads to a progressive decline in heat exchange capacity, which is one of the main causes of this temperature difference. In addition, uneven flow distribution among parallel flow channels further exacerbates the temperature differences among cells.

3.2.2 Tab Temperature Distribution

Tabs, as the current collection points of cells, concentrate Joule heat and are typical high-temperature regions within the battery. The maximum temperature difference in the tab region is 4.1°C, with the overall temperature difference smaller than that of the cell body surface. From the distribution pattern, there is an obvious temperature difference between positive and negative tabs, with a gradient distribution along the cell length direction. Although the tab temperature difference is lower than that of the cell surface, localized high-temperature points still require attention to avoid long-term overheating that may affect connection reliability and electrical performance stability.

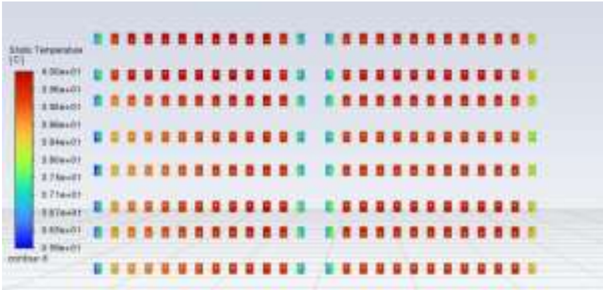

Figure 4 Temperature distribution contour map of tabs3.3 Cold Plate and Flow Channel

3.3Temperature Field Analysis

The liquid cold plate serves as the heat exchange medium between cells and the coolant. The temperature uniformity of its own surface is a prerequisite for ensuring uniform cell temperatures. Simulation results show that the maximum temperature difference across the entire cold plate reaches 8.3°C, and the overall temperature uniformity does not meet the ideal design standards. Due to the coolant absorbing heat and increasing in temperature, the plate surface temperature exhibits a gradient rise along the fluid flow path, with a low-temperature zone forming at the inlet side and high-temperature zones accumulating at the outlet side. At the flow channel bend locations, local heat exchange intensity fluctuates, generating multiple localized hot spots.

Excessive temperature difference in the cold plate itself will be directly transmitted to the cell bottom surfaces through the thermal interface materials, which is an important contributing factor to the large temperature differences on the cell surfaces. The current cold plate temperature difference of 8.3°C indicates that there remains considerable room for optimization in the flow channel layout.

The overall coolant inlet-outlet temperature difference is 3.2°C, which falls within a reasonable range, indicating that the current rated flow rate can basically match the total heat exchange demand of the battery pack. However, the spatial uniformity of coolant temperature distribution is still insufficient and requires further improvement through optimization of the flow channel structure and flow equalization design.

4 .CONCLUSIONS

A three-dimensional thermal simulation model of a 587 Ah 1P104S energy storage battery pack is established, and numerical simulation of the flow and heat transfer characteristics under rated operating conditions is performed. Based on the analysis of simulation results, the following conclusions and improvement directions are drawn:

(1) Performance evaluation of the current scheme: The flow resistance of the liquid cold plate, maximum battery temperature, and temperature differences of cells/tabs/cold plate all exceed the design specifications. The existing scheme cannot meet the design requirements.

(2) Flow resistance conclusion: The pressure drop of the current cold plate reaches 41.082 kPa, indicating excessive flow resistance that leads to serious pump power losses.

(3) Temperature uniformity conclusion: The temperature uniformity of both cells and the cold plate is poor. Uneven flow distribution among branches causes significant temperature differences on the plate surface, with risks of localized overheating.

(4) Overall optimization recommendations: Structural improvements should be carried out in three directions: flow channel topology optimization, flow distribution improvement, and heat exchange layout adjustment. After optimization, simulation verification should be conducted to compare the improvement amplitude of each indicator. Additionally, high-thermal-conductivity thermal pads and optimized assembly contact pressure should be employed to further enhance heat dissipation performance.

5.ACKNOWLEDGMENTS

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