Research on Liquid Cooling Pipeline Flow Mechanism based on Optimization of Battery Module Heat Dissipation Efficiency

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Abstract

Optimizing heat dissipation efficiency is a core challenge in the thermal management systems of new energy batteries and a key issue for ensuring the safety and stable performance of these batteries. With the increasing adoption of high-power fast-charging technology, current cooling solutions struggle to effectively handle the transient high thermal loads of battery packs, leading to intensified risks of local overheating and thermal runaway. Therefore, this study achieves efficient heat dissipation by integrating a design layout with threaded pipe structures. This paper introduces a power battery compartment cooling device based on composite synergistic cooling technology. The device realizes precise temperature control of the battery compartment through the combined effect of phase change material buffering, enhanced heat transfer via threaded liquid cooling pipes, and dynamic adjustment with variable-frequency energy-saving fans. This study not only improves battery cooling efficiency but also extends battery lifespan, reduces the risk of thermal runaway, and provides theoretical support for optimizing thermal management systems in new energy batteries.

Keywords

Liquid Cooling System; Fluid Circulation; Air Cooling; Piping; Numerical Simulation.

1. Introduction

With the development of the global new energy industry and the production of various new energy products, technology has now reached a new level. The new energy industry has become a core force driving sustainable development, with electric vehicles powered primarily by batteries playing a key role in addressing energy and environmental issues[1],However, some challenges come one after another. New energy batteries often generate a large amount of heat during charging and discharging. If this heat is not controlled, it could lead to a series of problems: the battery temperature continues to rise, causing thermal runaway and posing serious safety risks[2].Therefore, it is necessary to equip the battery pack with an efficient cooling system to ensure that the battery operates stably within an appropriate temperature range[3].Compared with other technologies for cooling new energy batteries, although different cooling methods are suitable for different application scenarios, liquid cooling is highly efficient, can precisely control the temperature, and maintain uniform heating of the battery pack[4],The coolant can also carry away heat as it flows through the circulation pipes driven by the liquid cooling pump. To achieve higher cooling performance for the cooling system, simulations of the flowing coolant and pipes were conducted using Flow Simulation in SolidWorks, and various planar diagrams were drawn using AutoCAD. Additionally, the overall structure of the battery assembly was optimized in SolidWorks. A key feature of this design is the use of a composite cooling architecture and threaded liquid cooling pipes, which can significantly enhance the cooling efficiency of new energy batteries, improve the performance of the battery cooling system, and contribute to the research on cooling of new energy batteries.

2. Design Analys

2.1 Composition of the Liquid Cooling System

This article introduces a power battery compartment cooling device based on composite synergistic heat dissipation technology to address the current low battery heat dissipation efficiency, which causes battery overheating.The cooling system includes: phase change material, phase change superheating plate, threaded liquid cooling pipe, threaded circulation heat dissipation pipe, variable frequency energy-saving fan, and liquid cooling circulation pump. The phase change material works together with the phase change superheating plate to absorb and store a large amount of heat, achieving efficient thermal management; the pipes adopt a threaded design and are connected to the liquid cooling circulation pump at both ends to ensure coolant circulation and improve flow rate; the variable frequency energy-saving fan is equipped with a dynamic heat dissipation mechanism, which can flexibly adjust the heat dissipation intensity according to different environmental conditions, ensuring effective cooling while reducing energy consumption and operating more smoothly. When heat is generated, it is conducted from the phase change material to the phase change superheating plate. The superheating plate initially transfers part of the heat to the casing, which is dissipated by the variable frequency energy-saving fan, while the majority of the heat is cooled by the coolant in the threaded liquid cooling pipes.

2.2 Working Principle

When the battery pack generates heat during operation, the heat is first transferred to the phase change material inside and below it for initial absorption and buffering. Subsequently, the heat is conducted to the phase change overheating plate. The phase change overheating plate transfers the heat downward to the threaded pipes. Driven by the liquid cooling circulation pump, the coolant flows through the threaded pipes, efficiently absorbing and carrying away heat through the significantly increased heat exchange area and internal turbulence effect. The heated coolant is then dissipated externally via the liquid cooling circulation pump. At the same time, the phase change overheating plate also conducts part of the heat upward to the enclosure walls, where airflow generated by a frequency-conversion energy-saving fan provides auxiliary air cooling to collectively maintain a stable temperature in the battery compartment.

2.3 Key Technology

This device adopts a composite cooling architecture, with the core being: phase change materials embedded in the battery pack to absorb and buffer heat, while the phase-change overheating plate conducts heat centrally, and a variable-frequency energy-saving fan provides auxiliary cooling for the enclosure; the main heat is efficiently removed by threaded liquid cooling channels, and our team's unique swirl design significantly increases the heat exchange area and enhances turbulence to raise the flow velocity. This design allows for reduced energy consumption while greatly improving thermal conductivity, ensuring both energy efficiency and high performance in the battery cooling process.

2.4 Structure Description

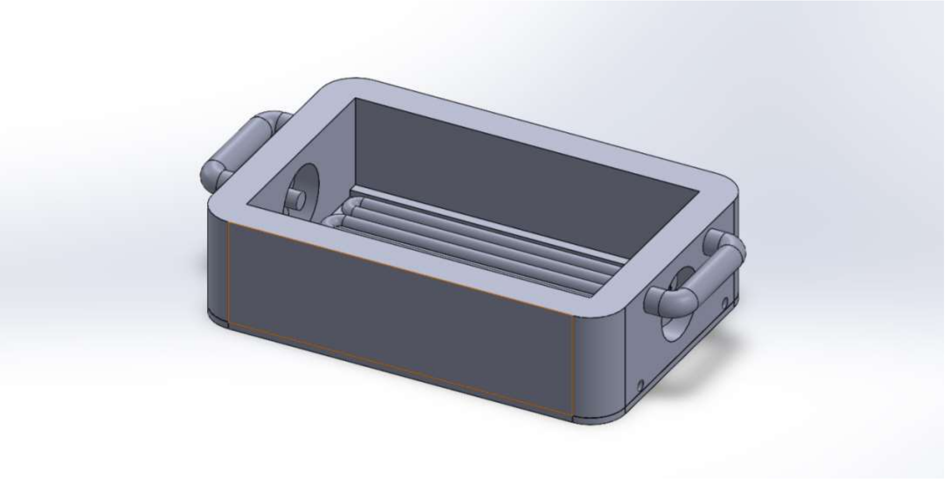

Figure 1. Device Diagram

As shown in Figure 1, the device is introduced in two parts regarding its structure.:

1) Liquid Cooling Circulation Mechanism

The liquid cooling mechanism is a multi-level heat dissipation system built around phase change materials, a phase change overheating plate, threaded liquid cooling pipelines, and a liquid cooling circulation pump. Each component works together through its physical position and function to achieve efficient thermal control. Phase change materials are embedded within the gaps of the battery pack, absorbing instantaneous heat generated during battery charging and discharging through the solid-liquid phase change process and storing part of that heat, forming the first level of temperature buffering. Its bottom is closely attached to a phase change overheating plate. This metal heat-conducting plate directs the residual heat from the phase change material downward, preventing vertical heat accumulation which could affect battery efficiency. The heat is then rapidly transferred from the phase change overheating plate to the horizontally integrated, thread-shaped liquid cooling pipeline embedded within the battery compartment support base-this is the core innovative design. The threaded flow channels extend the path of the cooling liquid and induce swirling turbulence, effectively breaking the thermal boundary layer, significantly improving heat conduction efficiency and heat exchange area. The more heat the battery pack dissipates, the higher the temperature of the cooling liquid. At this time, the enhanced heat transfer effect of the threaded pipe creates a positive feedback phenomenon: the higher the temperature, the faster the flow rate in the thread-shaped liquid cooling pipeline, enabling more rapid and efficient heat removal. The heated coolant, driven by the liquid cooling circulation pump on the side wall of the external casing, continuously circulates through the connecting pipelines: the high-temperature coolant is pumped to the heat dissipation zone at the edge of the casing to release heat, then returns cooled to the entrance of the threaded liquid cooling pipeline to absorb heat again in the next cycle, forming a closed-loop cooling system.

2) Air Cooling Mechanism

The air cooling mechanism consists of variable frequency energy-saving fans, symmetrically installed on both sides of the outer wall of the casing, with protective frames mounted on the outside to ensure safe operation. When the liquid cooling system malfunctions or temperature rises, preventing effective heat dissipation, the air cooling mechanism can quickly respond. The variable frequency energy-saving fan dynamically adjusts airflow, prioritizing the removal of internal heat through air cooling, speeding up internal air circulation and replacement in the casing, thereby reducing the overall device temperature. During the cooling process, the variable frequency fan can adjust the cooling intensity based on demand, reducing energy consumption to achieve energy-saving effects. This mechanism effectively prevents excessive heat accumulation on the battery surface, ensuring stable battery performance and normal operation, playing an important auxiliary role during heat dissipation.

3. Comparative Analysis

In this paper, Flow Simulation is used to simulate the pipeline of the liquid-cooled circulation mechanism in the battery compartment based on composite cooling technology, and the pipeline of the device is composed of two parts: liquid-cooled pipe and circulating heat dissipation pipe, which is S-shaped, and the outlet and inlet of the pipe are set on the same side to facilitate the circulation of coolant, and a cap with a thickness of 0.5mm is created at the inlet and opening to seal the internal volume, so that the fluid volume can be identified as the model. The coolant is released through the liquid-cooled circulation pump and the coolant is given a certain speed, so that it flows into the circulating heat dissipation pipe inlet, liquid-cooled pipeline, and circulating heat dissipation pipeline outlet in turn, so as to take away most of the heat of the phase change superheating plate.

When simulating, in order to ensure the accuracy of the calculation target results, the simulation parameters are set for ordinary pipes and threaded pipes:

Firstly, the pipeline material is set to aluminum (AL), the thermal condition of the outer wall is insulation wall, and the fluid type in the pipeline is water. Under the boundary conditions of the circulating heat dissipation pipeline, the inlet flow velocity is 3m/s, the thermodynamic parameter is 293.15K, the outlet environmental pressure is 101325Pa, the thermodynamic parameter is 353.15K, the boundary layer of the outlet and inlet of the circulating heat dissipation pipeline is turbulence, the turbulence intensity is 2%, and the turbulence length is 0.00048m. Secondly, the global meshing operation is carried out, the mesh type is automatic, the level of the initial mesh is four levels and the advanced channel refinement is opened, and the minimum gap size is 0.00364223816m. Finally, the global targets are set for ordinary pipes and threaded pipes: static pressure average, total pressure average, and velocity average.

The diameter of the circulating heat dissipation pipe and the liquid cooling pipe is 8mm, of which the liquid cooling pipe is 95mm long, and the circulating heat dissipation pipe is divided into two parts: inlet pipe and outlet pipe, of which the inlet pipe is 40mm long, and the outlet pipe is connected by two 50mm and 30mm at 90°.

In this paper, the experiment is iterated 300 times, and the target convergence is all the targets, so as to reduce the error and improve the accuracy of the calculated target results.

3.1 Comparison of Pipeline Type Adaptation Devices

Under the conditions set in this paper-pipe diameter of 8mm, water medium (20°C, $\mu=0.89\times10^{-3}$ Pa·s, $\rho=998.2$ kg/m^3), inlet velocity of 3 m/s, and outlet environmental pressure of 101325 Pa-by comparing ordinary pipes and threaded pipes in terms of flow uniformity, pressure loss, flow stability, and the majority of water velocity within the pipes, it can be concluded that threaded pipes are more suitable as the pipe type for the liquid cooling circulation system in battery compartments.

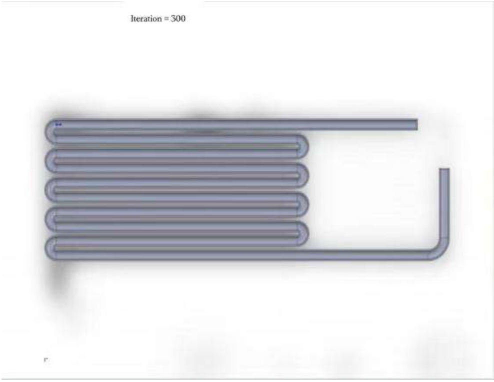

Figure 2. Schematic Diagram of a Common Pipeline Cross-section

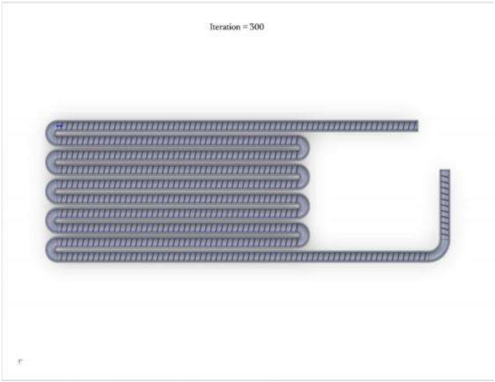

Figure 3. Schematic of Threaded Pipe Cross-Section

The simulation results for ordinary pipes and threaded pipes respectively show:

Table 1. Average pressure and average velocity of different pipes from the simulation results

Target (Value)	Ordinary liquid cooling pipeline	Threaded Liquid Cooling Pipe
Pipeline Average Static pressure 1 [Pa]	**132203.6412**	**379209.2385**
Pipeline Average Total pressure 2 [Pa]	**136750.0522**	**384590.8922**
Pipeline Average Speed 3 [m/s]	**2.994**	**3.163**

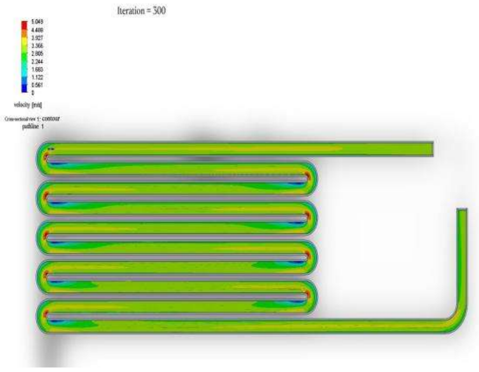

Figure 4. Velocity Gradient Distribution of Ordinary Pipe Cross-Section at the End of Simulation

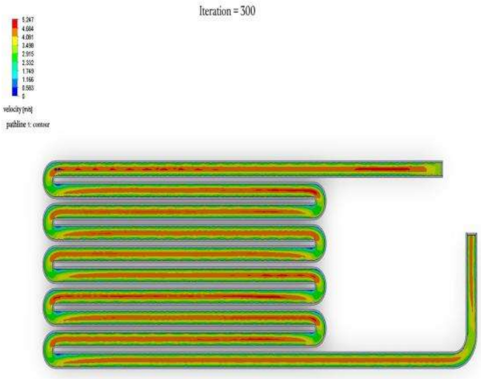

Figure 5. Velocity Gradient Distribution of Threaded Pipe Cross-Section at the End of Simulation

In the flow field characteristics of the ordinary pipeline shown in Figure 4, obvious low-speed zones (blue areas) appear, concentrated on the inside of pipe bends and in the middle of straight sections, indicating that fluid recirculation and vortices occur at these locations, causing a sharp drop in velocity (minimum around 0.561 m/s). The peak velocity (5.043 m/s) is lower than in Figure 5, the overall velocity distribution is more dispersed, flow stability is poor, and the low-speed areas are prone to heat accumulation, leading to local overheating and reducing the reliability of the liquid cooling system.

In the flow characteristics of the threaded pipe shown in Figure 5, the velocity distribution within the pipe is relatively uniform, with most areas showing yellow-green colors (medium velocity). Local red areas (such as the pipe bends and some straight sections) indicate peak velocities (around 5.247 m/s). There are no obvious low-speed zones at the bends, and fluid flows smoothly in the curved sections, indicating that under the given pipeline design/boundary conditions (such as inlet velocity and fluid viscosity), flow resistance is low, velocity decay is minimal, ensuring consistent heat dissipation and avoiding local overheating.

From this, it can be concluded that the uniformity of water flow velocity in threaded pipes and the absolute partial flow velocity are higher than in ordinary.

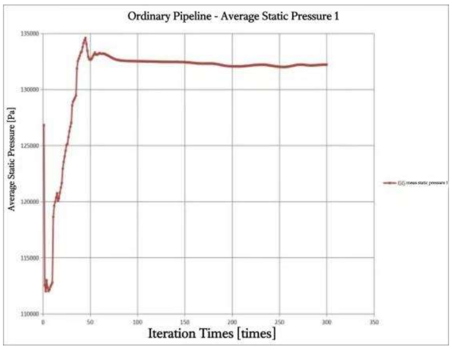

Figure 6. Average Static Pressure Line Chart of Water in Ordinary Pipes

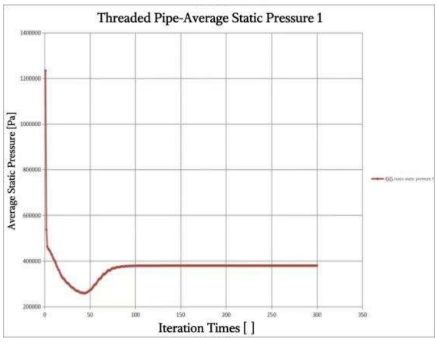

Figure 7. Average Static Pressure Line Chart of Water in Threaded Pipes

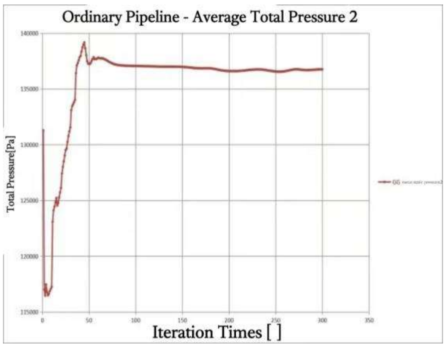

Figure 8. Average Total Pressure Curve of Water in Ordinary Pipe

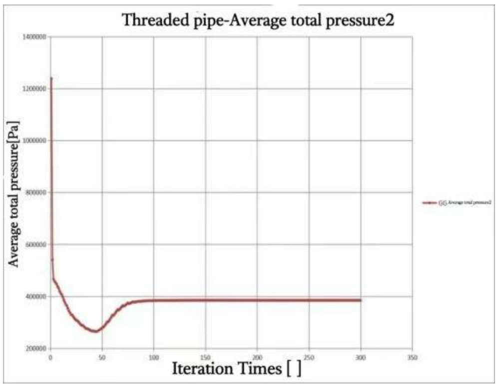

Figure 9. Average Total Pressure Curve of Water in Threaded Pipe

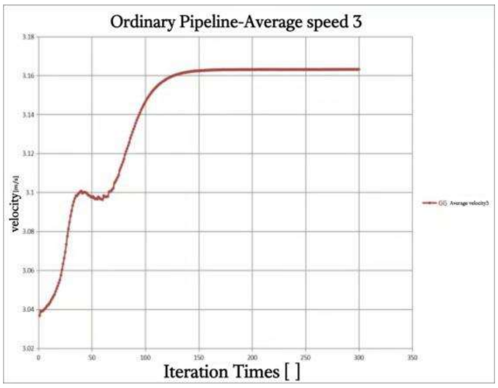

Figure 10. Average velocity line chart of water in ordinary pipes

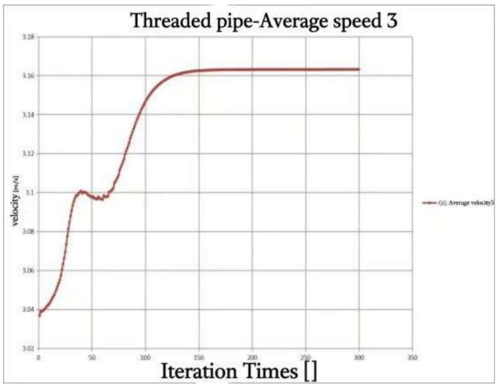

Figure 11. Average velocity line chart of water in threaded pipes

By comparing Figures 6, 7, 8, 9, 10, and 11, it can be seen that:

Flow Rate Uniformity (determines battery temperature differences)

Threaded pipe ≈ 3.16 m/s (after stabilization) with extremely uniform speed, allowing the coolant flow rate to be consistent within each battery module (avoiding localized overheating); ordinary pipe ≈ 2.99 m/s (after stabilization), with slight speed fluctuations and poor heat dissipation uniformity due to smoother flow.

Pressure Loss (Determines the Energy Consumption of the Cooling System)

Threaded Pipeline > 8×10^5 Pa (requires a high-pressure pump): Although it has high energy consumption, the strong turbulence and uniform flow rate can meet the cooling needs of battery packs under high-load conditions (such as fast charging and high-speed driving); Ordinary Pipeline ≈ 1×10^4 Pa (conventional pump): low energy consumption, but weak turbulence cannot handle the instantaneous high heat load of the battery pack (such as the rapid heat generation during sudden acceleration).

Flow Field Stability (Determines Battery Life)

Threaded Pipeline: Strong and stable turbulence; after 150 iterations, the flow field fully converges, with no obvious vortices or low-speed areas. It can continuously and stably remove battery heat over the long term, slowing battery aging (suitable for new energy vehicle scenarios with frequent start-stop and varied operating conditions).

Ordinary Pipeline: Although the flow field also converges, due to smoother flow, local heat accumulation easily occurs (such as at pipe bends and dead corners of the battery pack). Long-term operation accelerates battery degradation (especially in high-temperature environments, where the risk is higher).

4. Conclusion

This paper uses Flow Simulation to simulate the piping of a liquid cooling circulation mechanism in a battery compartment based on composite cooling technology, focusing on the effect of threaded liquid cooling pipes on heat dissipation performance. Based on the simulation results, improvements were proposed for the device piping, optimizing the liquid cooling system and the liquid cooling circulation mechanism. By leveraging the excellent flow field uniformity and enhanced turbulence effect of threaded pipes, the temperature of battery modules can be effectively controlled, better meeting the heat dissipation and temperature control requirements of battery modules under high-load operation, reducing the risk of thermal runaway, and extending battery service life, thereby improving the overall heat dissipation and thermal stability of battery modules. This study provides a theoretical basis and design reference for improving the heat dissipation efficiency and operational safety of battery packs, and holds certain engineering application value for the optimization of thermal management systems for new energy batteries.

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