

Flow Channel Design and Simulation of Cooling System for Lithium-Ion Battery Module

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Abstract. With the rapid growth of new energy vehicles, lithium-ion batteries have become the core power source due to their high energy density and long cycle life. However, severe heat generation during operation leads to high temperature and uneven distribution, which seriously affects battery performance, cycle life and safety. To address these issues, this study takes 18650 cylindrical lithium-ion batteries as the research object and designs three liquid cooling channels: serpentine, straight and rectangular. Using ANSYS FLUENT, computational fluid dynamics (CFD) simulations are conducted to analyze the effects of discharge rate, cooling plate structure, mass flow rate and ambient temperature on the thermal performance of the battery module. The results show that the serpentine channel provides the lowest maximum temperature and the smallest temperature difference, with a higher heat dissipation efficiency. Under 3C discharge, a mass flow rate of 0.08 kg/s meets the cooling requirement. This research offers a reliable reference for the design and optimization of liquid cooling systems for lithium-ion battery modules.

Keywords: Lithium-ion battery, Flow channel of cooling System, Thermal management

1. Introduction

Traditional fuel vehicle energy consumption and pollutant emissions have triggered severe energy and environmental issues, driving the rapid development of electric vehicles in recent years [1]. With new energy vehicles increasingly replacing fuel vehicles, lithium-ion batteries have become the mainstream power source due to high energy density, long service life and environmental friendliness. Nevertheless, these batteries are sensitive to temperature and only work reliably within 20°C–35°C. The confined layout and dense assembly of battery compartments severely restrict natural heat dissipation in electric vehicles [2]. Uneven temperature distribution and excessive temperature rise during battery operation accelerate aging and capacity fading, and may trigger thermal runaway, fire or explosion. Hence, efficient thermal management is indispensable for battery safety and stability.

Lithium batteries generate continuous heat during cycling; insufficient heat dissipation leads to temperature accumulation, performance deterioration, shortened lifespan and safety risks. Fluid cooling channel design is therefore vital for battery thermal management [3]. Operating temperatures outside the 20°C–35°C optimal range increase internal resistance and reduce efficiency. Proper fluid cooling effectively removes excess heat, maintains ideal operating

temperature, mitigates thermal degradation, extends battery life by 10%–20%, and suppresses thermal runaway hazards [4]. Moreover, uniform coolant flow achieved by well-designed cooling systems balances cell temperature, eliminates pack performance inconsistency, and improves overall operational safety and reliability. Numerous studies have optimized battery liquid cooling structures. Zhao et al. [5] proposed two optimization strategies based on serpentine corrugated flat tubes to improve battery pack temperature uniformity.

This study focuses on 18650 cylindrical lithium-ion battery modules and designs three different liquid cooling channel configurations. By adopting CFD simulations, the effects of discharge rate, cold plate structure, coolant mass flow rate and ambient temperature on the battery temperature, velocity and pressure fields are systematically investigated. This work aims to optimize the liquid cooling structure, improve the heat dissipation efficiency and temperature uniformity of battery modules, and provide reliable technical references for the thermal management design of electric vehicle power batteries.

2. Simulation of liquid cooled temperature field for 18650 lithium-ion battery module

In electric vehicle power battery systems, lithium-ion cells are assembled into integrated modules that continuously generate substantial heat during operation, resulting in a noticeable temperature rise. Accumulated heat cannot be dissipated promptly, which may cause the battery temperature to exceed the safe operating limit and further trigger thermal runaway, bringing severe safety risks. Furthermore, sustained high-temperature conditions greatly degrade the overall performance and cycle life of power batteries. Therefore, designing an efficient battery module heat dissipation system is crucial to ensure that the power battery operates within a safe temperature range, guaranteeing the range and power performance of electric vehicles [6].

2.1. Heat generation rate

Battery heating is an inevitable phenomenon in the process of electrochemical energy conversion. Accurately describing the thermal generation behavior of batteries is of great significance for the design of thermal management systems, safety performance evaluation, and life prediction. Bernardi et al. [7] proposed a formula for the heat generation power of batteries based on the assumption of a uniform and consistent temperature field inside the battery. This formula treats the battery as a uniform heat source, and the temperature changes over time, as shown in equation (1).

$$q = \frac{I}{V} \left[I (R_j + R_o) + T \frac{dE_{oc}}{dT} \right] \quad (1)$$

In the formula:

I : The working current of the battery (A) is positive during discharge and negative during charging;

V : Battery volume (m³);

E_{oc}/IR_j : Battery open circuit voltage (V);

IR_o : Battery operating voltage (V);

T : Battery working environment temperature (K);

dE_{oc}/dT : Temperature influence coefficient. Take its value as 0.0005.

Based on experimental data, the lithium-ion cells adopted in this work have a nominal capacity of 3000 mAh, a total volume of 21060 mm³ and an internal resistance of 50 mΩ. To simplify the model

and improve computational efficiency, the internal resistance is assumed constant in thermal analysis. Using material parameters and the thermodynamic formula in Equation (1), the volumetric heat generation rate of the battery is calculated at 1C, 2C and 3C discharge rates under an ambient temperature of 20 °C. The calculation results are detailed in Table 1.

Table 1. Heat generation rate per unit volume of lithium-ion battery

Discharge rate (C)	1	2	3
Discharge current (mA)	3000	6000	9000
Heat generation rate (W·m ⁻³)	53818	162069	324774

2.2. Modeling of flow channels

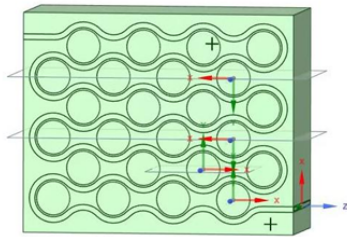


Figure 1. Serpentine shaped fluid channel for coolant

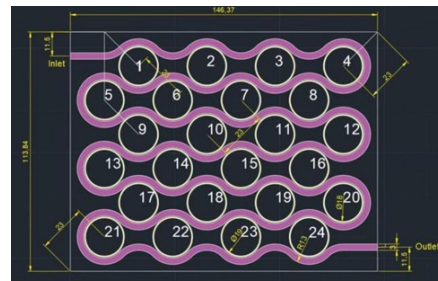


Figure 2. Schematic diagram of serpentine channel arrangement

Based on the serpentine channel liquid cooling structure, because of the complex internal structure of the battery pack, in order to improve computational efficiency, components that have a relatively small impact on the temperature field, such as fixing plates, bolts, wiring harnesses, etc., are ignored. Use FLUENT software to establish simulation models, partition grids, and perform transient calculations. Figure 1 shows the grid model of the liquid cooling structure of the battery pack. When there is no cooling structure, the battery pack is placed in the air domain and a free tetrahedral grid is used; when there is a liquid cooling structure, the flow of coolant fluid adopts the $k - \omega$ turbulence model [8]. The simulation adopts an inlet mass flow rate of 0.05 kg/s and a zero static pressure outlet, with a boundary layer defined at the coolant-channel interface. The coolant inlet temperature is set to 20°C, and natural convection with a heat transfer coefficient of 3 W/(m²·K) is applied to air-exposed surfaces. Based on the Bernardi equation, each battery cell is simplified as a uniform heat source for heat generation calculation. Besides, battery heat capacity and thermal conductivity are assumed constant, independent of ambient temperature and state of charge. There is experimental evidence that under this assumption, the error between the actual temperature rise of cylindrical lithium-ion battery cells and the simulated temperature rise is within an acceptable range, and the temperature rise trend is similar [9]. Therefore, it is believed that the established model basically conforms to the actual heat generation situation of the battery. The coolant is an aqueous solution. The coolant channel is made of aluminum alloy, and its thermal properties are assumed to be constant due to its small structural size, as shown in Figure 1 and Figure 2.

Similar to the above design, make the same settings for straight and rectangular channels, as shown in Figures 3 and 4.

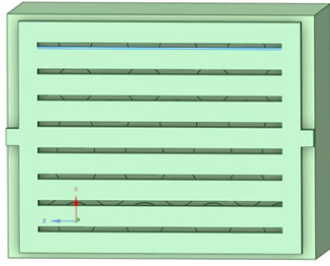


Figure 3. Direct channel for coolant

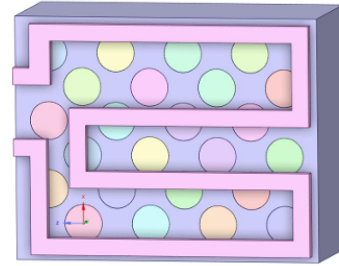


Figure 4. Rectangular channel for coolant

2.3. Simulation boundary condition setting

The flow and heat transfer characteristics of fluid channels directly affect the heat dissipation efficiency. Establishing accurate mathematical models is the foundation for optimizing heat dissipation design. The flow inside the fluid channel follows the laws of conservation of mass, momentum, and energy, and its governing equations are as follows:

(1) Continuity equation (conservation of mass)

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

ρ : density(kg/m³)

$\mathbf{u}$: velocity vector(m/s)

(2) Momentum equation (Navier Stokes equation)

$$\rho \left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) = -\nabla p + \mu \nabla^2 \mathbf{u} + \mathbf{F} \quad (3)$$

p : pressure (Pa)

μ : dynamic viscosity (Pa·s)

$\mathbf{F}$: body force

(3) Energy equation (first law of thermos dynamics)

$$\rho c_p \left(\frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T \right) = \nabla \cdot (\mathbf{k} \cdot \nabla T) + Q \quad (4)$$

T : temperature(K)

c_p : specific heat capacity(J/(kg·K))

$\mathbf{k}$: thermal conductivity(W/(m·K))

Q : heat source term(W/m³)

2.4. Setting of material parameters

This chapter uses the method of introducing liquid coolant to cool down the battery module. The thermal properties of the air are based on the default material air in the Fluent software database, and the physical model is selected as viscous (standard k- ϵ , standard wall function). The cold plate is made of aluminum alloy, which is the default material in the Fluent software database. The filling medium between batteries is a thermal conductive adhesive.

3. Analysis of simulation results of battery module

The third type of boundary condition refers to the known heat transfer coefficient between solid and fluid, as well as the fluid temperature, and the fluid-solid heat transfer problem in this paper belongs to this type, with the convective heat transfer coefficient set at $3 \text{ W}/(\text{m}^2 \cdot \text{K})$.

Upon completion of the simulation calculation, the results are analyzed using Fluent post-processing software to obtain the temperature cloud map of the battery module, as depicted in Figure 5. Fluent post-processing is utilized to analyze simulation results and acquire the temperature cloud map of the battery module. Under 3C discharge and a coolant mass flow rate of 0.05 kg/s , the module presents an uneven temperature rise among single cells. The maximum module temperature is 28.7°C at the top of the fifth column of batteries, while the minimum temperature is 20.1°C near the inlet and outlet, producing a maximum temperature difference of 8.6°C . Along the coolant flow direction, cell temperature gradually rises from the inlet to the outlet, with a markedly reduced temperature rise near the module outlet.

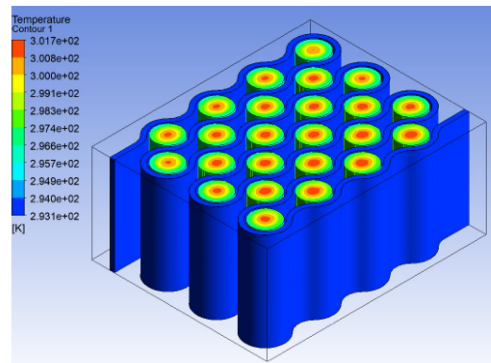


Figure 5. Temperature cloud map of battery module

The velocity cloud map inside the battery module is illustrated in Figure 6. The coolant velocity ranges from 0.2918 m/s to 0.5232 m/s . The small velocity difference reveals uniform flow and good continuity across the pack. High-velocity regions deliver satisfactory cooling performance matching practical demands, while low-velocity areas prevent local heat accumulation and reduce thermal runaway risks.

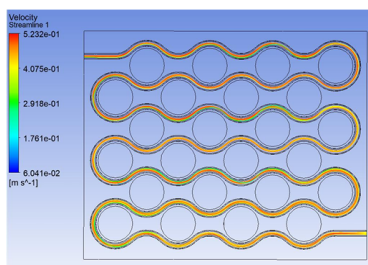


Figure 6. Speed cloud map of battery module

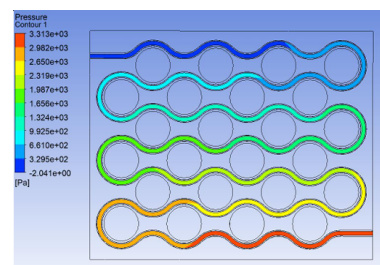


Figure 7. Battery module pressure cloud map

Observing the pressure cloud map in Figure 7, the pressure ranges from -2.041 Pa to 3313 Pa , indicating obvious pressure gradients in the cooling system. High pressure appears at the coolant inlet, narrow channels and high-resistance regions, with no reduction in local heat dissipation. Low pressure occurs at the channel outlet and vortex areas, where neither cavitation nor uneven coolant distribution is observed.

This chapter designs a parallel serpentine liquid cooling structure for 18650 lithium-ion battery packs to meet EV battery thermal management needs. Channel layout and cross-section are optimized for high-efficiency heat exchange. A 3D model is built in SolidWorks, and meshes with quality above 0.8 are generated. Using ANSYS Fluent with the k- ϵ model and coupled heat transfer algorithm, CFD simulations are carried out to analyze the battery pack temperature field under 3C discharge.

4. Conclusion

This study explores the liquid-cooling thermal performance of electric vehicle 18650 cylindrical lithium-ion batteries. A serpentine cooling channel is designed to stabilize battery operating temperature, enhance safety, and maintain stable driving range. According to the heat generation and heat transfer characteristics of batteries, a three-dimensional battery pack model is established and simulated via Fluent software. The temperature and velocity field distributions of the battery module and serpentine channel under different discharge rates are analyzed. Using the single variable control method, the influences of cold plate structure, coolant mass flow rate and ambient temperature on heat dissipation performance are investigated. The simulation results verify that the serpentine channel exhibits better cooling efficiency than straight and rectangular channels, and its structural design significantly affects the thermal management effect. This research can provide a reliable reference for the thermal optimization of electric vehicle power battery systems.

This article elaborates on the basic structure of lithium-ion batteries, detailing their internal composition, key structural parameters, and working principles. After comparing and analyzing three mainstream battery types, the study determined 18650 cylindrical batteries as the typical research object, and specifically listed the technical parameters of this model of battery. Based on the physical characteristics of 18650 batteries, a corresponding thermodynamic model was established to accurately calculate core thermophysical parameters, including specific heat capacity, material density, thermal conductivity, and heat generation rate. To verify the theoretical model, CFD simulation software FLUENT was used for numerical simulation. Through computer-aided analysis, visual measurement and evaluation of key parameters such as fluid motion state, temperature field distribution, and pressure changes in the battery system were achieved.

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