

STUDY ON COOLING OF BIONIC LEAF-VEIN CHANNEL LIQUID-COOLED PLATE FOR LITHIUM-ION BATTERY PACK

by

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In order to improve the cooling effect of lithium-ion battery packs, a bionic leaf-vein channel liquid-cooled plate was proposed. The liquid-cooled plate was numerically simulated using ANSYS FLUENT. The results show that at different Reynolds numbers, the pressure drop of the bionic leaf-vein channel is always smaller than that of the serpentine channel, and the local pressure drop of the bionic leaf-vein channel is 88.43% lower than that of the serpentine channel. The pressure drop of the bionic leaf-vein channel increases gradually with the increase of the branching angle, the branching angle increases from 35°-45°, and the pressure drop increases by 212.27 Pa. The Reynolds number increases from 500-7500, and the maximum temperature of the lithium-ion battery pack reduces by 3.74 K, and the maximum temperature difference reduces by 2.25 K.

Key words: thermal management system, bionic channel, liquid cooling strategy

Introduction

In recent years, the cooling requirements for heat generating devices in limited space have become higher and higher. Lithium-ion batteries (LIB) in electric vehicles (EV) and energy storage power stations are typical heat generating devices that require cooling in a limited space.

At present, the commonly used cooling methods mainly include air cooling, PCM cooling and liquid cooling. Air cooling has the advantages of low cost and high safety [1, 2]. However, due to the small specific heat capacity of air, it is difficult to take away a large amount of heat in a short time [3, 4]. The PCM will absorb a lot of heat during phase change to achieve the purpose of reducing the temperature of the cooled equipment. The PCM cooling has the advantage of lightweight and compact [5]. However, it is difficult to achieve the cooling effect by using PCM alone in a limited space [6, 7]. Although liquid cooling system has the possibility of leakage, the liquid cooling system can take away a lot of heat in a short time, which is suitable for the heat dissipation of equipment in limited space [8, 9].

The maximum temperature, T_{\max} , and maximum temperature difference, ΔT_{\max} , of the cooled equipment are important parameters to measure the cooling system. At the same time, the energy consumption of the cooling system itself is also an important standard to measure the cooling system. The liquid-cooled plate is an important part of the liquid cooling system, and its performance has a great impact on the cooling system. In order to improve the cooling

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capacity of the liquid cooling system and reduce the pressure drop of the liquid-cooled plate, many researchers have made many optimizations of the existing liquid-cooled plate or designed many new liquid-cooled plates. Kuang *et al.* [10] designed a micro pin-fin heat sink that can effectively improve heat transfer capacity and inhibit temperature rise. Ren *et al.* [11] designed a liquid-cooled plate with variable micro-channels to improve the temperature uniformity of the cooled object. The simulation and experimental results show that the liquid-cooled plate has better cooling performance. Koorata *et al.* [12] proposed a battery thermal management system (BTMS) based on micro-channel liquid-cooled plates, which can improve the temperature uniformity of soft pack batteries by more than 140%. Wang *et al.* [13] proposed a plate fin-and-tube heat exchanger with ring-bridge slit fins, and obtained the optimal fin structure by orthogonal experiment. Joshi *et al.* [14] computationally analyzed a passive heating system using fins and PCM and investigated the effect of different PCM thicknesses on heat transfer at low temperatures. Talele *et al.* [15] used a numerical model of thermal runaway to explain the evolution of the thermal runaway trigger point under different cathode chemical conditions under the influence of ambient temperature changes. Yang *et al.* [16] found that the cell temperature rise of solid-state batteries is mainly affected by reversible heat, and the heat of polarization is the largest contributor to the total heat generation of solid-state batteries. Chen *et al.* [17] developed a battery state-of-health estimation model based on convolutional neural networks, which can estimate the state-of-health of a battery from constant-current charge and discharge data. Subhedar *et al.* [18] conducted a study for immersion cooling system and found that $\text{Al}_2\text{O}_3/\text{EG}$ -water nanocoolant with a volume fraction of 4% or higher can maintain the battery temperature up to 50 °C.

A bionic leaf-vein channel liquid-cooled plate was designed to cope with the high T_{\max} and large ΔT_{\max} of LIB packs during high rate discharge. The microscopic flow in the channel of the bionic leaf-vein channel and the serpentine channel is analyzed to compare the pressure drop characteristics and cooling performance of the two liquid-cooled plates. The relationship between the branch angle of the bionic leaf-vein channel and the pressure drop was determined. The cooling performance of the bionic leaf-vein channel liquid-cooled plate is investigated under different Reynolds numbers, and different charge and discharge rates of LIB. To provide a reference for the future application of bionic channels or the application of bionic leaf-vein channel liquid-cooled plates in hybrid BTMS.

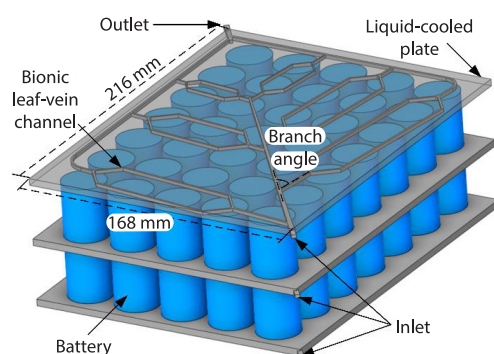


Figure 1. Bionic leaf-vein channel liquid-cooled plate system diagram

Numerical methods

The bionic leaf-vein channel liquid-cooled plate

Figure 1 is the schematic diagram of the bionic leaf-vein channel liquid-cooled plate. The bionic leaf-vein channel liquid-cooled plate is made of aluminum. The size of the bionic leaf-vein channel liquid-cooled plate is 168 mm × 216 mm, and the thickness is 4 mm. The size of the bionic leaf-vein channel liquid-cooled plate can be scaled according to the heat output and size of the cooled object. The channel in the liquid-cooled plate was designed with the leaf-vein channel as the prototype. The inlet and outlet of the channel are rectangular,

and the width of the channel changes gradually. The coolant flowing in the bionic leaf-vein channel uses an aqueous 50% concentration of ethylene glycol, which is more widely used today, and its thermophysical properties are shown in tab. 1.

Table 1. Thermophysical properties of coolant

Medium	ρ [kgm ⁻³]	c_p [Jkg ⁻¹ K ⁻¹]	k [Wm ⁻¹ K ⁻¹]	Dynamic viscosity [Pa·s]
Coolant	1071	3300	0.384	0.00103

Mathematical methods

In the numerical calculation, the following assumptions are made to simplify the calculation:

- The thermal resistance and thermal conductivity of the aluminum material in the bionic leaf-vein channel liquid-cooled plate are uniform.
- The physical properties of materials in numerical simulation are independent of temperature [19].

Based on the aforementioned assumptions, the transient heat transfer equation of the bionic leaf-vein channel liquid-cooled plate can be written:

$$\rho_b c_{p,b} \frac{\partial T_b}{\partial t} = k_x \frac{\partial^2 T_b}{\partial x^2} + k_y \frac{\partial^2 T_b}{\partial y^2} + k_z \frac{\partial^2 T_b}{\partial z^2} + Q \quad (1)$$

where ρ_b , $c_{p,b}$, and T_b are the density, specific heat capacity, and temperature of the battery, respectively. The Q is the heat generated by the lithium battery and t is the time and k_x , k_y , k_z are the heat transfer coefficients of the battery in the three directions x , y , z , respectively.

The flow process of coolant in the bionic leaf-vein channel is calculated according to the forced flow of incompressible fluid, and the physical process of flow heat transfer is represented by continuity equation, momentum conservation equation and energy conservation equation [20, 21].

Continuity equations for incompressible fluids:

$$\nabla(\rho_c \vec{v}_c) = 0 \quad (2)$$

Momentum conservation equation:

$$\frac{\partial}{\partial t}(\rho_c \vec{v}_c) + \nabla(\rho_c \vec{v}_c \vec{v}_c) = -\nabla P + \nabla(\mu_c \nabla \vec{v}_c) \quad (3)$$

Energy conservation equation:

$$\frac{\partial(\rho_c c_{p,c} T_c)}{\partial t} + \nabla(\rho_c c_{p,c} T_c \vec{v}_c) = \nabla(k_c \nabla T_c) \quad (4)$$

The Reynolds number is defined:

$$\text{Re} = \frac{\rho_c D \vec{v}_c}{\mu_c} \quad (5)$$

where ρ_c , $c_{p,c}$, \vec{v}_c , μ_c , T_c , k_c , P , and D are the density, specific heat capacity, velocity vector, dynamic viscosity, temperature, thermal conductivity, pressure of the fluid, respectively, and equivalent diameter.

The bionic leaf-vein channel in this study is a rectangular runner and its equivalent diameter should be obtained before performing the Reynolds number calculation. The equivalent diameter of the rectangle can be calculated according to eq. (6):

$$D = \frac{2ab}{a+b} \quad (6)$$

where a and b are the width of the rectangle and the height of the rectangle, respectively.

In this study the height of the inlet of the bionic leaf-vein channel is 2 mm and the width is 2.67 mm, and $D = 2 \times 2 \times 2.67 / (2 + 2.67) = 2.287$ mm. when the inlet flow rate of coolant is 0.21 m/s, $Re = 0.2 \times 2.287 \cdot 10^{-3} \times 1071 / 0.00103 = 500$. Using the same calculation method, $Re = 2500$ when the coolant inlet flow rate is 1.05 m/s. The $Re = 5000$ when the coolant inlet flow rate is 2.10 m/s. the $Re = 7500$ when the coolant inlet flow rate is 3.15 m/s.

Numerical calculation

The ANSYS FLUENT was used for numerical solution. The boundary condition of the inlet of the bionic leaf-vein channel is velocity inlet and the boundary condition of the outlet is pressure outlet. The inlet temperature of the coolant and the ambient temperature are both 298.15 K. The temperature of the return air at the outlet of the bionic leaf-vein channel is the ambient temperature. The interface between the LIB pack and air contact is set as natural-convection heat transfer, and the natural-convection heat transfer coefficient is 5 W/m²K. The coupling method of pressure and velocity is coupled. The pressure and velocity are coupled by the coupling method, and the discrete formats for pressure, momentum, energy and time are all second-order upwind formats. The surface of the coolant channel is set with a non-slip wall. The time step in the calculation is 1 second, and the number of steps is determined according to the time of one charge and discharge cycle at different charge and discharge multiples of 26650 LIB. (One charging cycle of 26650 LIB at 1C charging and discharging multiplicity is 4320 seconds).

The 3D Modelling with ANSYS SpaceClaim. The mesh was performed using FLUENT Meshing. The mesh types in the computational domain are all Polyhedral. the minimum Orthogonal Quality of the mesh is 0.38. In the working conditions of sections *Pressure drops characteristics of liquid-cold plate at different Reynolds number* and *Temperature characteristics of lithium battery pack at different Reynolds number*, the Reynolds number of the coolant in the bionic leaf-vein channel is greater than 2000 and the flow is turbulent. The standard $k-\epsilon$ model was used for turbulence modelling in the numerical simulation of turbulent flow conditions [11]. The value of y^+ near the wall is 81 for $Re = 7500$. y^+ near the wall is 53 for $Re = 5000$. The y^+ near the wall is 31 for $Re = 2500$.

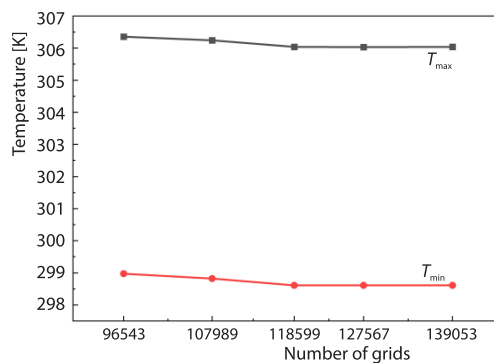


Figure 2. Grid independence verification

In order to ensure the accuracy and efficiency of the calculation, the number of grids is verified independently. Under the condition of $Re = 500$ and heat flux of the bionic leaf-vein channel liquid-cooled plate of 500 W/m², the number of grids of 96543, 107989, 118599, 127567, and 139053 were used to calculate, respectively. The T_{max} and T_{min} of the bionic leaf-vein channel liquid-cooled plate in the calculation are shown in fig. 2. It can be seen from fig. 2 that after the number of grids reaches 118599, the T_{max} and T_{min} of the bionic leaf-vein channel liquid-cooled plate hardly change after the number of grids continues to increase, so the number of 118599 grids is used for calculation.

Experimental verification

In order to ensure the accuracy of the numerical simulation, the experimental method is used to verify the numerical simulation. The schematic diagram of the experiment is shown in fig. 3, and the physical diagram is shown in fig. 4. The PI heating film with internal resistance of 8Ω (produced by Shenzhen Sanying New Material Technology Co., LTD.) is used to generate heat according to the calorific value of 26650 LIB pack to replace the heat of the LIB pack. High power programmable DC power supply (produced by Hangzhou Lanyi Electronics Co., LTD.) supplies power to PI heating film. The *K*-type thermocouple measures the temperature in the middle of the liquid-cooled plate. The data acquisition instrument transmits the collected temperature data to the computer. The cistern is filled with coolant and a submersible pump is placed as a power device.

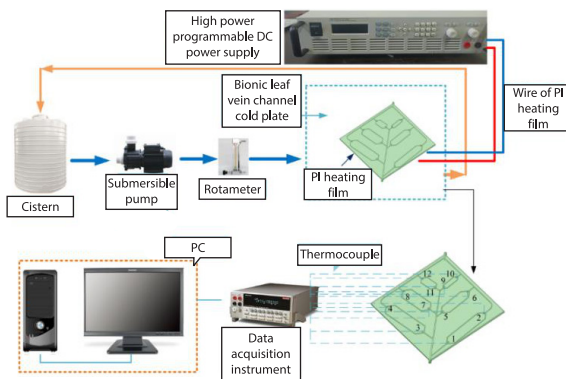


Figure 3. Experimental schematic diagram

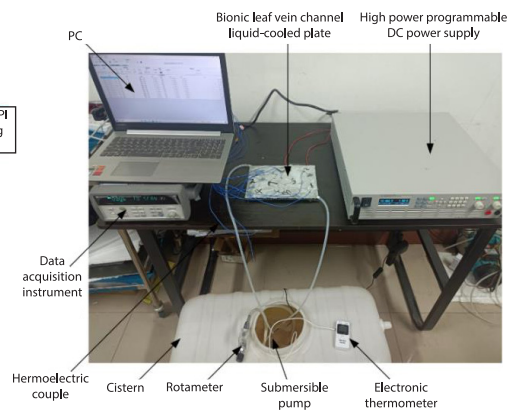


Figure 4. Physical diagram of experimental device

The liquid-cooled plate is formed by pasting and fixing two parts after processing, respectively. The liquid-cooled plate is formed by pasting and fixing two parts after processing, respectively. The upper part of the liquid-cooled plate is made of acrylic material. And the bionic leaf-vein channel is engraved on it by computer numerical control (CNC) engraving. The lower part of the liquid-cooled plate is an aluminum plate of the same shape and size as the upper part but without the channel. One side of the aluminum plate is bonded with the acrylic plate, the other side is affixed with the PI heating film. The position where the PI heating film meets the air is affixed with thermal insulation material. A total of 12 temperature measuring points are arranged on the liquid-cooled plate. On the acrylic plate, the corresponding position of the measuring point has a round hole, and the temperature probe of the thermocouple is placed in the round hole to measure the temperature at the interface of the acrylic plate and the aluminum plate, that is, the central section of the liquid-cooled plate.

The temperature variations at 12 measurement points during the experiment measured using the *K*-type thermocouple and the Keysight model 34972A data acquisition instrument (with a measurement error of 0.1%) are shown in fig. 5(a). The temperatures at the end of discharge at 12 measurement points in the middle plane of the liquid-cooled plate obtained by numerical simulation and experiment were compared under the working condition of 500 W/m^2 of heat production, and the results are shown in fig. 5(b). The trend of the temperature obtained from experiment and numerical simulation is consistent, and the maximum difference is 2.05°C , with an error of 7.23%. After experimental verification, the accuracy of numerical simulation can be guaranteed.

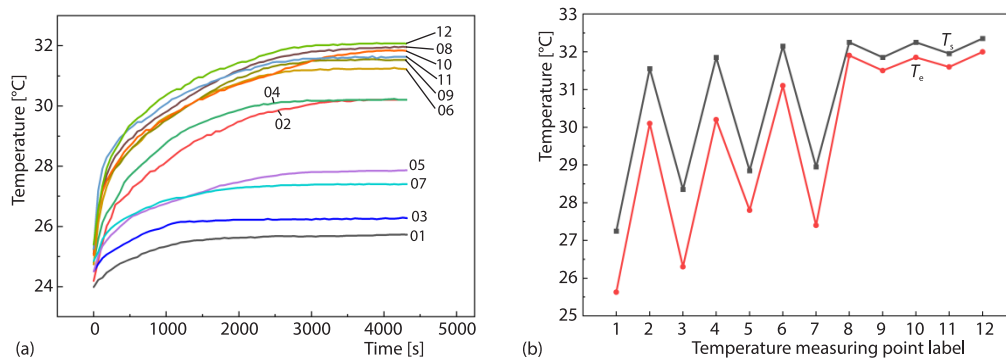


Figure 5. Temperature change and comparison between experimental and simulated

Results and discussion

Pressure drops characteristics of liquid-cooled plate at different Reynolds number

According to the balance between the heat generated by the LIB and the heat taken away by the coolant, Reynolds number is set at 500. In order to investigate the quantitative relationship between Reynolds number and pressure drop, the Reynolds number was enlarged by 5, 10, and 15 times, respectively. Figure 6 compares the pressure drop of bionic leaf-vein channel liquid-cooled plate and serpentine channel liquid-cooled plate with almost the same channel heat transfer area at different Reynolds number (bionic leaf-vein channel liquid-cooled plate: 10835 mm², serpentine channel liquid-cooled plate: 9990 mm²). When $Re = 500$, the pressure drop of serpentine channel liquid-cooled plate is 2.19 kPa, that of bionic leaf-vein channel liquid-cooled plate is 0.99 kPa, and the pressure drop of bionic leaf-vein channel liquid-cooled plate is 45.21% of that of serpentine channel liquid-cooled plate. When $Re = 7500$, the pressure drop of serpentine channel liquid-cooled plate is 101.74 kPa, that of bionic leaf-vein channel liquid-cooled plate is 58.39 kPa, and the pressure drop of bionic leaf-vein channel liquid-cooled plate is 57.39% of that of serpentine channel liquid-cooled plate. In the process of increasing Reynolds number, the pressure drops of the bionic leaf-vein liquid-cooled plate is always smaller than that of the serpentine channel liquid-cooled plate. The Reynolds number increases by 15 times from 500-7500, while the pressure drop of the serpentine channel liquid-cooled plate increases by 46.46 times and that with bionic leaf-vein channel liquid-cooled plate increases by 58.98 times. The increasing factor of pressure drop of bionic leaf-vein channel liquid-cooled plate and serpentine channel liquid-cooled plate is much larger than that of Reynolds number. Under the premise of meeting the cooling requirements, the value of the smaller Reynolds number should be preferred.

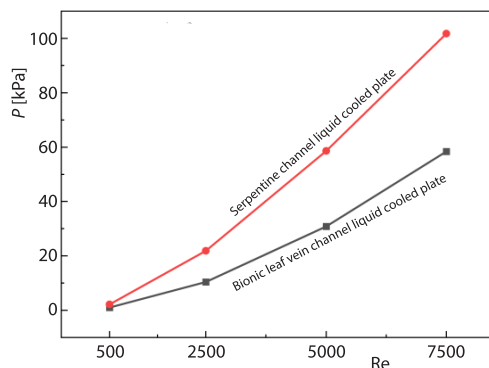


Figure 6. Pressure drop at different Reynolds numbers

This section explores the reason why the pressure drop of the bionic leaf-vein channel liquid-cooled plate is smaller than that of the serpentine channel liquid-cooled plate. The flow resistance is composed of running resistance and

local resistance. The proportion of local resistance in the total resistance is much higher than that of running resistance. The pressure drop of liquid-cooled plate is mainly affected by local resistance. The local resistance of the serpentine channel is mainly generated at the bend of the channel. Figure 7(a) shows the flow velocity cloud diagram in the serpentine channel liquid-cooled plate when the $Re = 5000$. Due to the effect of centrifugal force, except for the boundary-layer, the velocity away from the center of the curve is larger, and the velocity near the center of the curve is smaller. Figure 7(b) shows the flow velocity cloud diagram in the bionic leaf-vein channel when $Re = 5000$ and branch angle is 45° . The local resistance of the bionic leaf-vein channel mainly appears in the branches of the channel. At the branch angle of the incoming flow direction, the velocity of the coolant is small. A relatively long-distance region with low velocity is formed near the wall of the branch angle of the incoming flow direction. The width of this region increases first and then decreases. An area of higher flow velocity is formed for a short distance at the branching angle in the direction of outflow. When the $Re = 5000$, the pressure drops of the coolant flowing through the first U -shaped bend in the serpentine channel is 2.42 kPa, and the pressure drop flowing through the first branch angle of the bionic leaf-vein channel is 2.14 kPa. The local pressure drop of the bionic leaf-vein channel is 88.43% of the local pressure drop of the serpentine channel. It is precisely because of the different flow state of the coolant at the local resistance of the channel that the different pressure drop characteristics of the two liquid-cooled plates are formed.

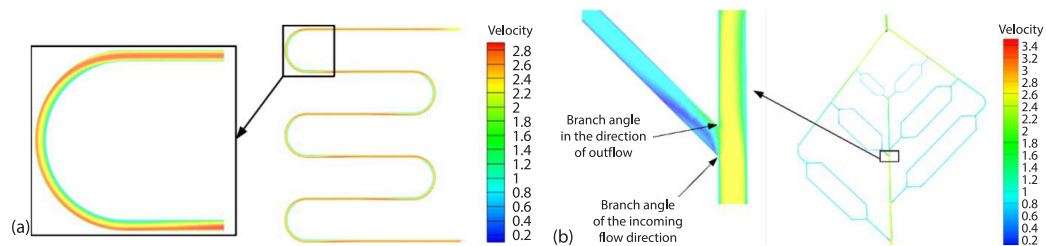


Figure 7. Flow cloud image of coolant; (a) coolant flow cloud image in the serpentine channel and (b) coolant flow cloud image in bionic leaf-vein channel

Pressure drops characteristics at different channel branch angles

It can be seen from fig. 8 that the pressure drop of the bionic leaf-vein channel liquid-cooled plate gradually increases with the increase of the branch angle of the bionic leaf-vein channel. When the branch angle of the bionic leaf-vein channel liquid-cooled plate increases from 42.5 – 45° , the increase of pressure drop of the bionic leaf-vein channel liquid-cooled plate is much larger than the increase of other branch angles.

The phenomenon in fig. 8 was explored by intercepting the channel at the first branch angle of the bionic leaf-vein channel near the inlet of the channel to form a tee pipe of the same diameter and length as the tube in the bionic leaf-vein channel. The pressure drop of tees with different branch angles was investigated by CFD, and the results are shown in fig. 9. As the branch angle increases, the resistance

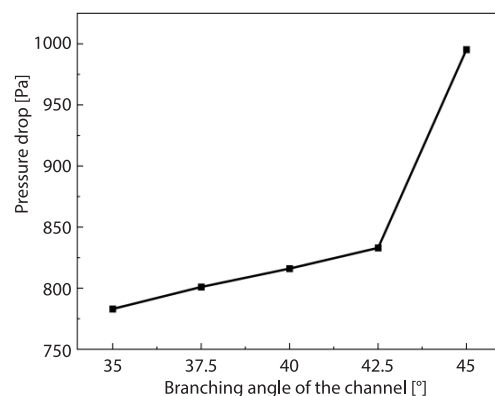


Figure 8. Pressure drop at different branch angles

of the tee pipe also increases and the trend is the same as that of the resistance of the bionic leaf-vein channel with the branch angle. When the inlet flow rate of the coolant is the same, it can be considered that the running resistance of the tee pipe with different branch angles is the same, and the change trend of the pressure drop of the tee pipe can reflect the change of the local resistance of the tee pipe.

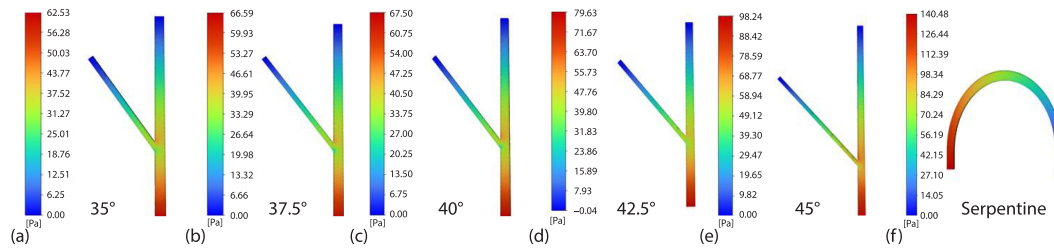


Figure 9. Pressure drop diagram for the tee pipes

To sum up, with the increase of the branch angle, the local resistance at the branch of the channel increases. However, the proportion of local resistance in the flow resistance is much higher than that of running resistance. Therefore, it is shown that the pressure drops of the bionic leaf-vein channel liquid-cooled plate changes with the change of local resistance, and the local resistance increases with the increase of the branch angle of the bionic leaf-vein channel. Therefore, the pressure drops of the bionic leaf-vein channel liquid-cooled gradually increases with the increase of the branch angle of the bionic leaf-vein channel.

Temperature characteristics of lithium-ion battery pack at different discharge rates

This section explores the temperature characteristics of LIB packs with different discharge rate (1C, 2C, 3C, 4C) under the cooling of bionic leaf-vein channel liquid-cooled plate. The C is used to indicate the charging and discharging multiplication of a LIB and is a measurement of the charging and discharging current relative to its rated capacity. This group first charges the LIB pack by constant current charging in the preliminary experiments, and when the charging cut-off voltage of the LIB pack is reached, constant voltage charging is performed on the LIB pack to eliminate the polarization voltage. After the preliminary experimental measurements obtained 26650 LIB in 1C, 2C, 3C, and 4C charging and discharging multiplicity of the average heat power of 0.5 W, 0.8 W, 1.3 W, and 2.1 W, respectively [22]. In the use of FLUENT numerical simulation process will be measured experimentally in the process of LIB heat generation data loaded into the LIB pack of the solid domain. The 26650 LIB used in this paper is a lithium iron phosphate (LiFePO_4) battery, the positive material of the battery is LiFePO_4 , and the negative material is carbon. The nominal voltage of the LIB is 3.2 V, the maximum charge voltage is 3.65 V, and the internal resistance of the LIB measured at AC1kHz of 50% state of charge (SOC) is 20 m Ω . The electrolyte of lithium LIB is mainly composed of lithium hexafluorophosphate (LiPF_6), solvents and additives. The physical property parameters of 26650 LIB are shown in tab. 2.

Table 2. The 26650 lithium battery physical properties

Medium	ρ [kgm^{-3}]	c_p [$\text{Jkg}^{-1}\text{K}^{-1}$]	k [$\text{Wm}^{-1}\text{K}^{-1}$]	Diameter [mm]	Height [mm]
Battery	2218	1033	1.01/3.91	26	65

The BTMS should ensure that the temperature of the LIB during the charging and discharging process is controlled at 295.15-318.15 K. Excessive temperature difference between different cells in the LIB pack may lead to thermal imbalance [23, 24]. The BTMS must also ensure that the ΔT_{\max} between different cells in the LIB pack is less than 5 K, which is crucial for the performance and safety of the LIB pack [25, 26].

When the ambient temperature is 298.15 K and $Re = 2500$, the highest temperature of the LIB pack at different charge and discharge rates is shown in fig. 10(a). With the increase of charging and discharging rate, the T_{\max} of 26650 LIB pack gradually increases, but the T_{\max} always meets the requirements of the highest temperature during the charging and discharging process of the LIB pack. The T_{\max} of LIB pack increased from 300.11 K to 306.37 K when the charge and discharge rate increased from 1C-4C under bionic leaf-vein channel liquid-cooled plate cooling, with an increase of 18.84%. It can be seen from fig. 10(b) that during this process, the ΔT_{\max} of the LIB pack increases from 1.68-7.06 K, an increase of 76.2%. When using bionic leaf-vein channel liquid-cooled plate for LIB pack cooling, increasing the charging and discharging rate of the LIB pack results in a much larger multiplier increase in the ΔT_{\max} of the LIB pack than in the T_{\max} . The ΔT_{\max} of the LIB pack is more than 5 K at 4C charging and discharging rate.

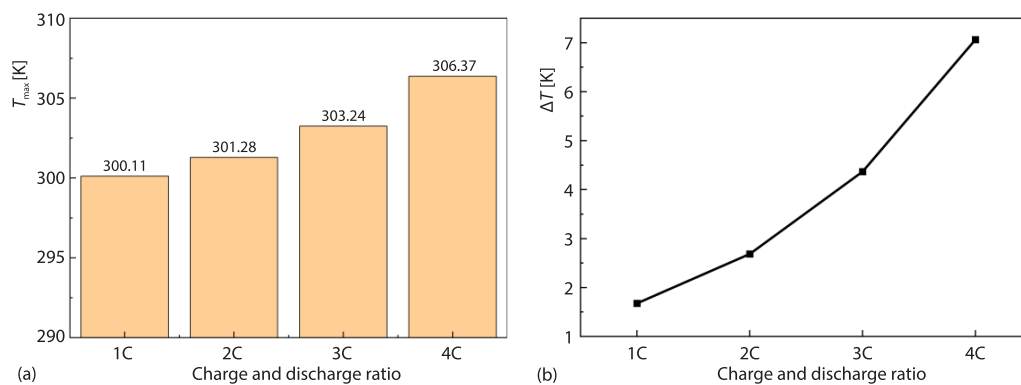


Figure 10. Temperature of battery pack at different charge and discharge ratios; (a) maximum temperature graph and (b) maximum temperature differences

Temperature characteristics of lithium-ion battery pack at different Reynolds number

The Reynolds number affects the temperature of the cooled LIB pack by affecting the flow pattern of the coolant in the channel of the liquid-cooled plate. The relationship between the Re and the temperature of the LIB pack was investigated at the ambient temperature of 298.15 K and the 26650 LIB 2C discharge multiplier.

From figs. 11(a) and 11(b), it can be seen that with the increase of Reynolds number, the T_{\max} and T_{\min} of the LIB pack are gradually reduced, but the magnitudes are all decreasing. The T_{\max} of the LIB pack when the $Re = 500$ is in line with the T_{\max} requirements of the LIB pack at work. The T_{\max} of the LIB pack is almost the same in the first 250 seconds of the charging and discharging process under different Reynolds number. The T_{\min} decreases with the increase of Re from the beginning of the charging and discharging process.

From fig. 11(c), it can be seen that with the increase of Reynolds number the ΔT_{\max} of the LIB pack will gradually decrease. The decrease in the amplitude of the same will gradu-

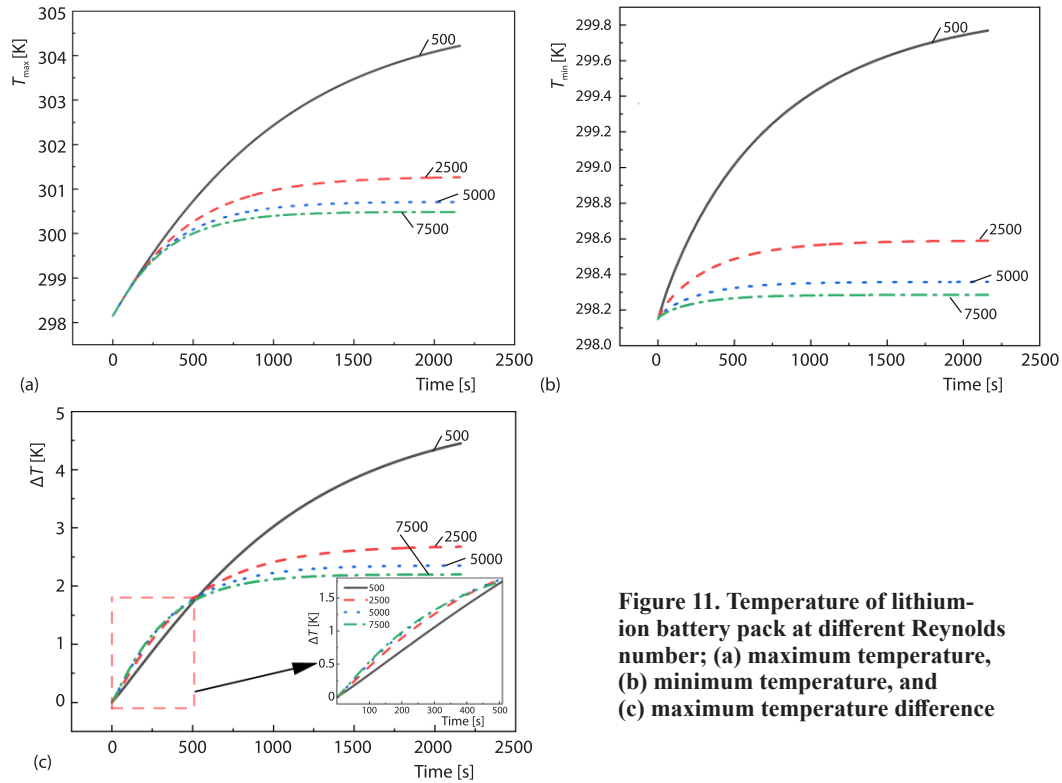


Figure 11. Temperature of lithium-ion battery pack at different Reynolds number; (a) maximum temperature, (b) minimum temperature, and (c) maximum temperature difference

ally decrease. When the $Re = 500$, it still meets the ΔT_{max} requirement of LIB pack. In the first 500 seconds of the charging and discharging process, the larger the Reynolds number, the larger the ΔT_{max} of the LIB pack. The main reason for this phenomenon is that the T_{max} of the LIB pack corresponding to different Reynolds number in the early charge and discharge process is almost the same, while the T_{min} gradually decreases with the increase of Reynolds number, which leads to the difference between the T_{max} and the T_{min} of the LIB pack in the early charge and discharge process with the increase of the Reynolds number. This leads to the battery charging and discharging process in the early stage of the highest temperature and the lowest temperature difference with the increase in Reynolds number, that is, the ΔT_{max} between the LIB pack with the increase in Reynolds number and increase. With the increase of the Reynolds number, the pressure drop of the liquid-cooled plate will increase rapidly, in the smaller Reynolds number can meet the cooling requirements of the cooled object should be prioritized to choose the smaller Reynolds number.

Comparison of performance with serpentine channel liquid-cooled plate

This section compares the cooling capacity of the bionic leaf-vein channel liquid-cooled plate and the serpentine channel liquid-cooled plate. The T_{max} and T_{min} of 26650 LIB pack cooled by the bionic leaf-vein channel liquid-cooled plate and serpentine channel liquid-cooled plate are shown in fig. 12(a) at both coolant and ambient temperatures of 298.15 K and a Reynolds number of 2500. The T_{max} of the LIB pack cooled by the bionic leaf-vein channel liquid-cooled plate gradually decreases with the increase of the branch angle. The T_{max} of

the LIB pack cooled by the serpentine channel liquid-cooled plate is higher than the T_{\max} of the LIB pack cooled by the bionic leaf-vein channel liquid-cooled plate for all branch angles. From fig. 12(b), the ΔT_{\max} of the LIB pack cooled by the bionic leaf-vein channel liquid-cooled plate is lower than that of the LIB pack cooled by the serpentine channel liquid-cooled plate when the branching angles of the bionic leaf-vein channel liquid-cooled plate are 40° , 42.5° , and 45° .

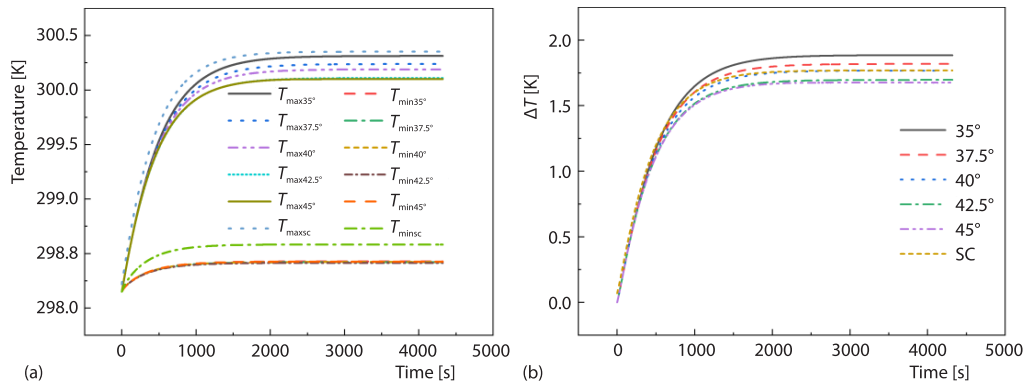


Figure 12. Comparison of cooling capacity with serpentine channel liquid-cooled;
(a) maximum temperature and minimum temperature and
(b) maximum temperature difference

The T_{\max} of the LIB packs cooled by the bionic leaf-vein channel liquid-cooled plate are lower than those of the LIB packs cooled by the serpentine channel liquid-cooled plate. Compared with the serpentine channel liquid-cooled plate, the bionic leaf-vein channel liquid-cooled plate can reduce the T_{\max} and the ΔT_{\max} of the LIB packs. From section *Pressure drops characteristics of liquid-cold plate at different Reynolds number*, the pressure drop of the bionic leaf-vein channel liquid-cooled plate is less than that of the serpentine channel liquid-cooled plate. The cooling performance and pressure drop characteristics of the bionic leaf-vein channel liquid-cooled plate are better than those of the serpentine channel liquid-cooled plate.

Conclusions

With experimental validation, the following conclusions are drawn from numerical calculation studies.

- When the branch angle of the bionic leaf-vein channel increases from 35° - 45° , the pressure drop of the bionic leaf-vein channel increases gradually with the increase of the branch angle of the channel. When the branching angle of the bionic leaf-vein channel is increased from 42.5° - 45° , the increase in the pressure drop of the bionic leaf-vein channel is much larger than the increase in the other branching angles.
- At an ambient temperature of 298.15 K and a LIB charging and discharging multiplication rate of 2C, the bionic leaf-vein channel liquid-cooled plate is able to meet the temperature requirements of the LIB pack when $Re = 500$. With the increase of Reynolds number, the T_{\max} and the ΔT_{\max} of the LIB pack gradually decrease.
- The cooling performance and pressure drop characteristics of the bionic leaf-vein channel liquid-cooled plate are better than those of the serpentine channel liquid-cooled plate.

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Nomenclature

c_p – heat capacity, [Jkg⁻¹K⁻¹]
 D – equivalent diameter, [mm]
 k – heat transfer coefficient, [Wm⁻¹K⁻¹]
 Q – heat production rate, [Wm⁻³]
 Re – Reynolds number [$\rho_c D_c v_c / \mu_c$], [–]
 T – local temperature, [K]
 T_{\max} – maximum temperature, [K]
 T_{\min} – minimum temperature, [K]
 ΔT_{\max} – maximum difference in temperature, [K]
 t – time, [s]

Greek letters

Δ – difference
 ρ – density [kgm⁻³]

Subscripts

b – battery
 c – coolant
 e – experiment

Acronyms

BTMS – battery thermal management system
 CNC – computer numerical control
 EV – electric vehicle
 LIB – lithium-ion battery pack
 SOC – state of charge

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