Simulation Study on Liquid Cooling of Lithium-ion Battery Pack with a Novel Pipeline Structure

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Abstract. Lithium-ion battery is widely used as the mainstream power source of electric vehicles owing to its high specific energy and low self-discharge rate. However, the performance of the lithium-ion battery is largely hindered by its heat dissipation issue. In this paper, lithium-ion battery pack with main channel and multi-branch channel based on liquid cooling system is studied. Further, numerical simulation was used to analyze the effects of coolant temperature and flow rate on cooling performance. Based on the original pipeline structure, a new pipeline structure was proposed in the present work. The results show that increasing the coolant flow rate not only reduces the maximum temperature of the battery pack, but also reduces the temperature difference. Lowering the coolant temperature could largely decrease the maximum temperature of the battery pack, but it tends to widen the temperature difference and worsen the temperature uniformity. Upon comparison, maximum temperature is found to be decreased by 0.44K, whereas, the temperature difference of the battery decreased and the temperature uniformity is improved.

1. Introduction

The world regards electric vehicles have the greatest potential in the 21st century [1,2]. Among all the batteries which powers the electric vehicles, lithium-ion battery is considered as the mainstream power source to replace petroleum fuel due to its high specific energy and low self-discharge rate [3]. However, heat will be generated during the working process of lithium-ion batteries, which leads to the rise in working temperature of batteries. If the heat doesn’t dissipate effectively in a working lithium-ion battery, the heat would accumulate and the battery temperature will gradually increase [4]. When the self-heating rate of a battery or battery pack is greater than a certain threshold value, then it would leads to a catastrophic problem of thermal runaway, even rupture and explosion [5,6]. Hence, it is significant to maintain the maximum temperature of battery within a safe range and lower the temperature inhomogeneity.

Presently, the cooling methods adopted for the lithium-ion based power battery pack for electric vehicles are air cooling, liquid cooling and phase change material (PCM) cooling [7]. An advanced air cooling system with double silicon cooling plate coupled with copper mesh was proposed by Li et al [8]. The influences of the thickness of silicon cooling plate and wind speed on the cooling effect were studied through experiments and simulations. Wei et al. [9] designed an efficient air cooling system method that comprehensively considers the volume and cooling performance of the battery system. However, the efficiency of the air cooling system is low, whereas, the temperature reduction degree and uniformity are significantly poor. Weng et al. [10] investigated the effect of PCT and PCM thickness of solid paraffin on battery temperature. It was found that the safer operating temperature could be ensured by
the lower phase transition temperature, however, it downsizes the capacity of the battery. In addition, if the thickness of PCM module was too large, the heat generated may not dissipate in time, leading to the accumulation of heat, and even heat hazards.

Comparing to air cooling and PCM cooling, liquid cooling is relatively more efficient due to its high heat transfer capability, which leads to a better cooling effect. Due to the better cooling effect and cooling temperature uniformity of liquid cooling, some battery manufacturers are already started to use liquid cooling instead of air cooling. Dong et al. [11] proposed a novel double helix cooling pipeline based on a 18650 lithium-ion battery and analyzed the effects of coolant mass flow rate on cooling performance. They found that, an increase in mass flow rate is an effective method to lower maximum temperature and temperature difference, if the mass flow rate is below a certain value. However, increase in mass flow rate will limit the improvement of cooling performance brought by the increased mass velocity. A cellular liquid cooling jacket for thermal management based on 21700 lithium-ion battery cells was developed by Sheng et al [12]. They used numerical simulation method to investigate the effects of channel dimension and fluid flowing on the heat distribution of cells. Their results show that the temperature standard deviation is lower and the thermal distribution is more even with interlaced flow directions.

In general, the pipeline structure is either single main channel or multiple main channels, however, the pipeline structure with main channel connecting multiple branch channels is relatively few, and the research on this kind of pipeline structures are lacking. Furthermore, the influence of the flow parameters (shape and size of the pipeline) and the coolant parameters (temperature and flow rate), on cooling effect are still unclear and needs to be studied further.

In this work, a battery liquid cooling system with a main channel connecting multiple branch channels was proposed and simulation analysis was carried out. Influence of different coolant flow rate and temperature on cooling performance was also studied.

2. Model description

The 3D model of the battery cooling system is shown in Fig. 1. The battery pack consists of 24 single cells with the length × width × height of 112 × 42 × 167 mm. The heat generated by the battery is a solid heat source. Since, the battery pole ear has little influence on this study, the aspects of battery pole ear has been ignored. The battery pack is supported by an aluminum cooling plate, which is in contact with the cooling plate directly. Aluminum is preferred as the cooling plate material due to its light weight and high thermal conductivity [13]. Thickness of the cooling plate is 45mm, diameter of the main pipe in the cooling plate is 25mm and the diameter of the separate pipe is 15mm. The cooling plate has a cooling channel where the coolant is loaded. The front end of the cooling plate is provided with two round holes with a diameter of 15mm, which is the coolant inlet and coolant outlet, respectively. The heat generated by the battery will be carried away by the flow of coolant through the cooling channel. The properties of each part of the cooling system are shown in Table 1, and the structural design of the cooling channel in the cooling plate is shown in Fig. 2.

| Table 1. The properties of each component. |
|-------------------------------------------|
| **Content** | **Density (kg/m³)** | **Specific heat capacity (J · kg⁻¹ · K⁻¹)** | **Coefficient of thermal conductivity (W · m⁻¹ · K⁻¹)** |
| Ethylene glycol aqueous solution | 1027.93 | 3826 | 0.503 |
| Cooling plate | 2707 | 892 | 160 |
| Battery | 1676 | 1100 | 2.7 |
3. Initial boundary conditions

The set 3D model was imported into the Mesh for meshing, and the grid model was obtained as illustrated in Fig. 3. The total number of grids is 315838. The boundary conditions were set as follows: According to the working state of the battery pack, the heating rate of each battery is set as 4142 W/m³. While setting up boundary conditions, inlet and outlet is set to velocity and pressure, respectively, with a hydraulic diameter of 25mm. The pressure at the pressure outlet is always set at 1Pa. The cell surface is set as a convective heat transfer boundary, and the heat transfer coefficient under natural convection is set as 3W/(m².K). The ambient temperature is 298K.

4. Theoretical model

The temperature distribution inside the battery can be described by the energy conservation equation of the cell inside, as shown in Eq. (1):

\[ \rho c_p \frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x} \left( \kappa_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \kappa_y \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( \kappa_z \frac{\partial T}{\partial z} \right) + Q_v. \]  

(1)

Where, \( \rho \) and \( C_p \) is the density of the cell and specific heat capacity of the cell, respectively; \( \kappa_x, \kappa_y, \) and \( \kappa_z \) are the thermal conductivity in the directions of x, y and z respectively; \( Q_v \) is the volumetric heat source generated by electrochemical enthalpy change and internal resistance in the battery [14], and the expression of \( Q_v \) is shown in Eq. (2)

\[ Q_v = \left[ -I \frac{\partial E}{\partial T} + I(E - U) \right] / V \]  

(2)

Where \( I \) is the current during charge and discharge; \( V \) is the volume of the battery; \( E \) is the open circuit voltage of the battery; \( U \) is the working voltage of the battery; \( \frac{\partial E}{\partial T} \) is the temperature effect coefficient, which is set as 0.00022 \( V / K \); \( T \) is the battery temperature; \( Q_v \) is the rate of heat generation.

The coolant used in this work is ethylene glycol aqueous solution. The energy conservation equation of the coolant is given in Eq. (3):

\[ \rho c \frac{\partial T_c}{\partial t} + \nabla \cdot \left( \rho c \nabla T_c \right) = \nabla \left( \frac{K_c}{C_c} \nabla T_c \right) \]  

(3)
Where, $\rho_c$ is the density of the coolant; $C_c$ is the specific heat capacity of coolant; $K_c$ is the thermal conductivity of the coolant.

5. Results and discussion

Fig. 4, Fig. 5 and Fig. 6 are obtained through simulation calculation, and the results have been verified with previous reference [15]. The temperature distribution cloud diagram of the battery pack is illustrated in Fig. 4. From the diagram, it can be seen that the battery is cooled well near the cold plate side with a temperature of about 298K, which is almost close to the set temperature. However, maximum temperature was observed away from the side of the cold plate with the temperature of 309.08K. This shows that battery is cooled poorly when it is away from the side of cold plate. The reason for poor cooling is that, the battery is not in direct contact with the cold plate and the distance from the cold plate is far, hence the cooling effect of the cold plate cannot be fully played.

According to the analysis of Fig. 5, the heat exchange between the cooling medium and the battery occurs when the cooling medium flows in the cooling pipeline. As the temperature increases, the heat transfer coefficient becomes smaller which results in weaker cooling performance. For fluid analysis, in addition to the temperature field of the fluid, pressure field of the fluid should also be considered. Fig. 6 shows the pressure field of the fluid. Fluid pressure loss is an important indicator to evaluate the power of the pump, if the pressure difference is greater, then the pump power needed will be higher. The pressure loss of the fluid is estimated as 57.28Pa.

5.1. Influence of coolant flow rate

The inlet velocity was set as 0.2m/s, 0.4m/s and 0.8m/s, whereas, all the other conditions remain unchanged. Simulation analysis was conducted to obtain the fluid pressure cloud diagram, as shown in Fig.7 to Fig. 8. The obtained results have been verified with previous results [15]. Further, the obtained
results were imported into the post-processing software of CFD-Post. The temperature value of 10000 points of the battery pack is extracted by using the sample method with equal space spacing, and its standard deviation is calculated.

Table 2. Standard deviation of battery pack temperature at different flow rates

| Flow rate (m/s) | 0.2 | 0.4 | 0.8 |
|----------------|-----|-----|-----|
| Standard deviation | 3.12 | 3.17 | 3.22 |

From Fig. 9, it is evident that if the flow rate increases from 0.2m/s to 0.4m/s, the maximum temperature of the battery pack decreases from 309.08K to 308.91K. However, the minimum temperature remains unchanged and the temperature difference decreases by 0.17K. Similarly, when the flow velocity increases from 0.4m/s to 0.8m/s, the maximum temperature of the battery decreases from 308.91K to 308.78K. This leads to a drop in temperature difference by 0.13K and the minimum temperature remains same. Hence, by increasing the flow rate both the maximum temperature and the temperature difference could be reduced. A group of simulations with flow rates of 1m/s, 2m/s and 4m/s were added, and the temperature conditions at all flow rates were analyzed together, and the obtained results are shown in Fig. 9. When the flow rate increases, the temperature of the battery pack does not decrease rapidly, however the decline slows with the increasing flow rate. This indicates that the liquid can have a good cooling effect at a low flow rate. As the flow rate increases, the standard deviation of temperature also gets surged, but the increasing trend in temperature gradually slows down. This specifies that, deterioration of overall temperature under the influence of flow rate decreases with the increasing flow rate. A lower flow rate will effectively cut down the requirements on equipment and energy consumption, hence the selection of an appropriate flow rate needs to be analyzed on a case-by-case basis.

The pressure loss of fluid is an important index which cannot be ignored. According to the combined analysis of Fig. 6, Fig. 7 and Fig. 8, when the flow rate increases in multiples, the pressure loss of the fluid increases from 57.28Pa to 229.87Pa and then to 909.23Pa, which is close to doubling. This will increase the requirements of more pump power and cold plate technology, which results in increased manufacturing cost. The change of fluid pressure should be taken into account while selecting the velocity.
5.2. Influence of coolant temperature

The coolant with low temperature changes the cooling plate temperature by directly touching the cooling plate and thereby lowering the battery temperature. However, the equipment requirements for manufacturing batteries will be increased. This section reports the influence of different temperature coolant on heat dissipation under the condition that other parameters are unchanged. Table 3 shows the physical properties of ethylene glycol aqueous solution at different temperatures.

The inlet temperature was set as 293K and 303K, respectively, and all the other conditions remain unchanged. Fig. 10 and Fig. 11 shows the temperature cloud diagram of the battery pack derived from simulation analysis and the results have been verified with the earlier results. Then the obtained results were imported into the post-processing software of CFD-Post, and the temperature value of 10000 points of the battery pack is extracted by using the sample method with equal space spacing, and its standard deviation is calculated.

Based on Fig. 6, Fig. 10 and Fig. 11, it is observed that coolant with temperature 293K, 298K and 303K has the maximum temperature of 307.12K, 309.08K and 310.77K, respectively. Whereas, the minimum temperature is approximately close to the set temperature, the temperature difference is estimated as 14.12K, 11.08K and 7.77K, respectively, and the standard deviation is calculated to be 4, 3.12 and 2.24, respectively. It can be concluded that, using a lower temperature coolant could reduce the maximum temperature, but lead to an increase in temperature difference and affects the overall temperature uniformity. Moreover, usage of a lower temperature coolant will raise the requirements for the refrigeration system and increase energy consumption. Thus, the maximum temperature, temperature difference and overall temperature uniformity as well as energy consumption should be considered before selecting the temperature of the coolant.
Table 3. Properties of ethylene glycol aqueous solutions at different temperatures

| Temperature (K) | Density (kg/m³) | Specific heat capacity (J·kg⁻¹·K⁻¹) | Coefficient of thermal conductivity (W·m⁻¹·K⁻¹) | Viscosity×10⁻³ (Pa·s) |
|-----------------|-----------------|-------------------------------------|-----------------------------------------------|-----------------------|
| 293             | 1029.72         | 3815                                | 0.497                                         | 1.65                  |
| 298             | 1027.93         | 3826                                | 0.503                                         | 1.46                  |
| 303             | 1026.02         | 3838                                | 0.509                                         | 1.3                   |

5.3. Influence of new pipeline structure design

This section takes this as a starting point, and proposes a new pipeline structure design. The contact area between the cold plate and the coolant has been increased to make the temperature of the cold plate as consistent as possible, and thereby achieving the maximum cooling effect of the cold plate on each battery. The proposed pipeline structure design is shown in Fig. 12. Without changing the conditions, simulation was carried out to get the cloud diagram of battery temperature, as shown in Fig. 13. Further, standard deviation was calculated by importing the obtained result into the post-processing software of CFD-Post, and the temperature value of 10000 points of the battery pack is extracted by using the sample method with equal space spacing.

By comparing Fig. 12 and Fig. 13, it is found that by using the proposed new pipeline structure design, the maximum temperature is 308.65K with a temperature difference of 0.44K. The temperature standard deviation is estimated as 3.02, which means that the overall temperature uniformity of the battery pack is improved. It can be intuitively seen from the figure that, comparing to the previous design the difference in the maximum temperature area of each battery is improved. By analyzing the fluid pressure cloud diagram, it is observed that the fluid pressure loss of the two pipeline designs is not very different, so there is no need of additional requirements for pumps.

Therefore, increasing the contact area between the coolant and the cold plate not only reduces the maximum temperature, but also reduce the temperature difference of the battery. It improves the overall temperature uniformity of the battery pack, and produce a better cooling effect on the battery pack.

6. Conclusion

(1) Increasing the coolant flow velocity reduces the maximum temperature of the battery pack as well as the temperature difference. Maximum temperature does not decrease in multiples when the flow rate doubles from 0.2m/s. Drop in maximum temperature occurred when the flow rate increased from 0.2m/s to 0.4m/s, with a decrease of 0.17K. According to the fitting curve, when the flow rate increases to more than 4m/s, the cooling effect has not greatly improved upon continuous increase of flow rate.

(2) Lowering the coolant temperature greatly reduces the maximum temperature of the battery pack. A 293K coolant was able to reduce the maximum battery temperature by 1.94K. But, it enlarged the temperature difference and also decreased the temperature uniformity.

(3) A new pipeline structure design is proposed. By changing the shape of the pipeline, the contact area between the cooling plate and the coolant have been increased. The maximum temperature...
decreased by 0.44K with the application of the new pipeline structure, and the temperature difference of the battery decreases. The calculated standard deviation of the temperature is 3.02, which indicates the improved temperature uniformity of the battery when compared to the original structure. The proposed structure design does not increased the pressure loss of the fluid in the pipeline, hence additional requirement of the pump can be avoided.

Acknowledgments
This research was supported by the National Natural Science Foundation of China (51904069).

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