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Research Paper

Structural optimization of lithium-ion battery pack with forced air cooling system

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HIGHLIGHTS

- Single factor analysis is performed for the heat dissipation performance.
- CFD simulation results are validated by comparing with the experimental results.
- Orthogonal design method is used to optimize the structure of the battery pack.

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ABSTRACT

The forced air cooling system is of great significance in the battery thermal management system because of its simple structure and low cost. The influences of three factors (the air-inlet angle, the air-outlet angle and the width of the air flow channel between battery cells) on the heat dissipation of a Lithium-ion battery pack are researched by experiments and computational fluid dynamics (CFD) simulations. Then the three structure parameters are optimized by using single factor analysis and orthogonal test method. It is shown that the layout of the air flow channels has great impacts on the maximum temperature and the temperature difference. The best cooling performance is obtained under the condition of 2.5° air-inlet angle, 2.5° air-outlet angle and equal channels width. With the optimization method, the maximum temperature and the temperature difference are decreased by 12.82% and 29.72% respectively. Therefore, the presented approach in this paper is able to optimize the battery thermal management system for electric vehicles.

1. Introduction

In recent years, due to the rise of the environmental problems, such as the global warming and the energy depletion, the Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs) are drawing attentions from governments and automobile groups around the world. The Lithium-ion battery has gradually replaced other kinds of batteries as the main power of the EVs [1]. However, the lithium-ion battery generated a large amount of heat due to the Joule effect of its inner resistance and the chemical reaction during charging and discharging processes [2]. If the heat could not be dissipated timely and quickly during moving of the EVs, it resulted in over-high temperature and uneven temperature distribution, which contributed to the degradation and failure of batteries [3,4]. Moreover, the phenomenon of thermal runaway might lead to serious consequences, such as fire and explosion, and the thermal safety, reliability, and balance of Lithium-ion batteries were essential to the usability and safety performance of the EVs [5]. Therefore, the investigation of the battery thermal management (BTM) should be paid more attentions in the future [6–8].

The following cooling methods of the battery pack had been implemented in the engineering problems: the air cooling [9–11], the liquid cooling [12–14], the phase change materials (PCM) cooling [15,16] and the heat pipes [17,18]. The air cooling was divided into the nature air cooling and the forced air cooling [19,20]. The forced air cooling system [21] had been widely used for the BTM system. Researchers had carried out a large numbers of investigations on the heat dissipation of the battery pack. Xu and He [22] researched the heat dissipation performance of different airflow duct modes. The results indicated the thermal performance was

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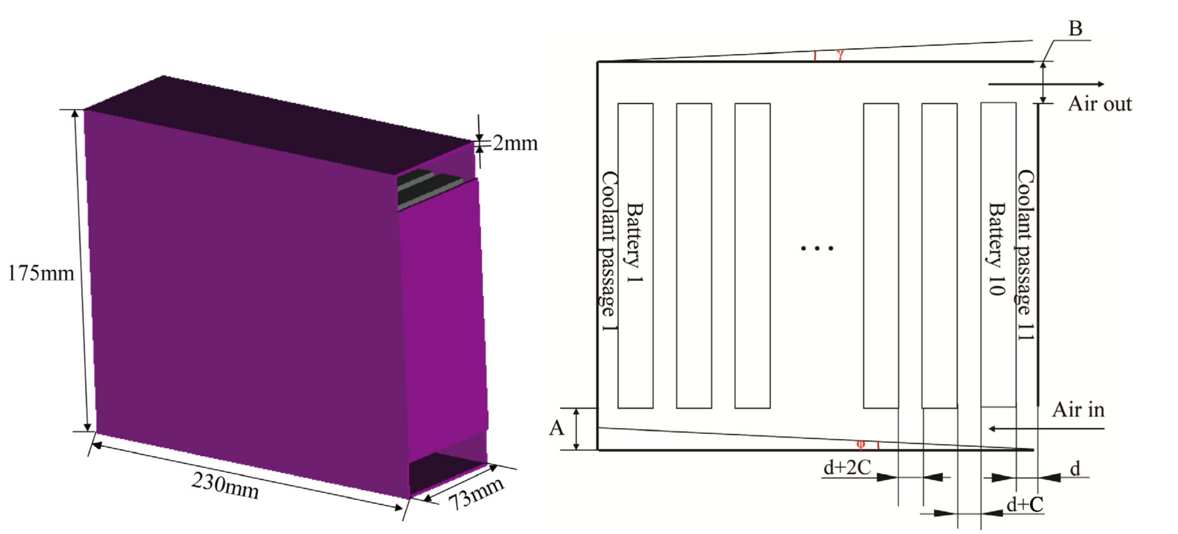
improved by changing the longitudinal battery pack into the horizontal battery pack. Park [11] demonstrated the required cooling performance could be achieved by employing tapered manifold and pressure relief ventilation. Sabbah et al. [23] compared the effectiveness of the phase change materials with the forced air cooling. Kizilel et al. [16] investigated the passive cooling approach with cooling the PCM to prevent the thermal runway propagation.

Many optimization methods had been employed for the thermal management design of the forced air cooling. Deng et al. [24] designed a novel thermal management structure for the HEV Lithium-ion battery pack. The CFD temperature field analysis showed that the thermal management structures performance was interior to the parallel thermal management structures. Yu et al. [25] proposed an air-flow-integrated thermal management system to dissipate the heat generation and uniform the distribution of temperature in the lithium-ion batteries. Liu et al. [26] increased the inlet and the outlet areas of the battery pack, such that the air flow could enter the channel width between cells of the battery pack, which led to a better heat transfer coefficient. Yang et al. [27] used the software Fluent to study the effects of structure on the battery thermal performance. Several different heat dissipation structures were determined by different inlet angles and velocities. Fan et al. [28] found that lowering the channel widths or increasing the flow rate air mass could decrease the maximum temperature. However a moderate size of the channel width was necessary to improve the temperature uniformity. Wang et al. [29] investigated the thermal performance of battery modules by installing fans in different positions and changing the cell arrangements under the same air cooling condition. Hwang et al. [30] studied the effects of different factors, such as the channel widths and the ventilation locations of the inlets and outlets among the battery cells, on the rate of the heat dissipation and the temperature distribution in the battery packs.

In this paper, we first optimize the structure of the air cooling by using the orthogonal design method. Here the influential factors of the Lithium-ion battery temperature performance include the air inlet angle, the air outlet angle and the layout of the air flow channel between battery cells. The battery surface temperature and the temperature difference in simulations coincide with the experiment results, which verify the reliability of CFD simulation analysis method. Numerical simulation is conducted to analyze the temperature distribution in the battery pack and the air flow distribution in the coolant passages. Then the air cooling structure is optimized by the single-factor analysis method and the orthogonal test method based on three design factors mentioned above. The optimal combination levels of factors are obtained from the range analysis. The single-factor analysis method and multiple-factor analysis design method are used to optimize the air cooling structure for lowing the maximum temperature and the temperature difference of the battery pack. The best thermal performance is achieved under the condition of 2.5° air-inlet angle, 2.5° air-outlet angle and evenly-spaced battery cells. The air cooling effects of the optimal condition is improved greatly when compared with the initial condition. The maximum temperature and the temperature difference are dropped by 12.82% and 29.72%, respectively, after the multi-objective optimization.

2. Design for the air flow configuration

The battery pack is composed of 10 battery cells and 11 coolant passages in a row. The dimension of a battery cell is 16 mm × 65 mm × 131 mm. The overall dimension of the battery system is 230 mm × 73 mm × 175 mm (length × width × height). And the thickness of the plate of the box is 2 mm, as shown in Fig. 1(a). The heights at the air-inlet and the air-outlet areas are the same in the initial air cooling structure, 20 mm. The gap between battery cells is 6 mm in the initial case. The geometry of the air flow passage is shown in Fig. 1(b). The width of the passage 11 is denoted with d. The width is increased by C in the passage on the left. Thus the widths in passage 10 and passage 9 are $d + C$ and $d + 2C$ respectively, as shown in Fig. 1(b). The width in passage 1 is $d + 10C$. The value of C can be used to control the distance distribution of the batteries. In the initial case, the distance between each battery is constant, thus the value of C is zero. When the value of C is 0.5 mm and the width of the passage 1 is 8.5 mm, the widths from passage 1 to passage 11 are 8.5 mm, 8 mm, 7.5 mm, 7 mm, 6.5 mm, 6 mm, 5.5 mm, 5 mm, 4.5 mm, 4 mm and 3.5 mm respectively.



(a) 3D model of the battery pack

(b) Battery pack profile structure, *A* is the height at the end of air-inlet area, *B* is the height of air-outlet manifold, *C* is the tolerance value

Fig. 1. The battery pack of the air cooling system of the simulation model.