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Structure optimization of parallel air-cooled battery thermal management system

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ABSTRACT

Battery thermal management system (BTMS) is critical to battery packs in electric vehicles, which significantly influences the service life of the battery packs and the performance of the electric vehicles. In this paper, the structure optimization of the parallel air-cooled BTMS is investigated to improve the cooling performance of the system. The flow resistance network model is introduced to calculate the velocities in the cooling channels of the system. The numerical results show that the velocities in the cooling channels calculated by the flow resistance network model are in good agreement with the ones calculated by CFD method, validating the effectiveness of the model. Furthermore, the model can save much calculation time, which is applicable to combine with the optimization approaches for structure optimization of BTMS. Subsequently, the structure of the BTMS is optimized through arranging the widths of the inlet divergence plenum and the outlet convergence plenum without changing the layout of the battery cells. Newton method is introduced to combine with the flow resistance network model to obtain the optimal plenum widths, with the target of minimizing the standard deviation of airflow velocities in the cooling channels. The optimization with fixed inlet flow rate and the one with fixed power consumption are both conducted. Three-dimensional CFD calculations for both the original BTMS and the optimized BTMS are performed, respectively. The results show that the cooling performance of the BTMS can be improved significantly after optimization using the proposed method. For the situation with fixed inlet flow rate and constant heat generation of the battery pack, the maximum temperature difference of the battery pack is reduced by 45% after optimization. For the situation with fixed power consumption and constant heat generation of the battery pack, the maximum temperature difference of the battery pack is reduced by 41% after optimization. Moreover, the maximum temperature of the battery pack is also reduced slightly after optimization. For the situation with fixed power consumption and unsteady heat generation of the battery pack, the maximum temperature differences of the battery pack are still reduced by 35% and 32% respectively for 4C and 5C discharge processes after optimization. It can be concluded that Newton method combined with the flow resistance network model is an effective method to optimize the structure of the parallel air-cooled BTMS and to improve the cooling performance of the system.

1. Introduction

Under the pressure of energy shortage and environmental protection, the development of electric vehicles (EVs) and hybrid electric vehicles (HEVs) has attracted worldwide attention in recent years. The performances of the EVs and HEVs are significantly influenced by the performance of battery packs. A large amount of heat will be generated when the battery packs work, especially for the situations that the vehicle starts or accelerates. If the generated heat cannot be ejected quickly, the temperature of the battery packs will increase rapidly. Finally, the high temperature will damage the battery packs or even cause explosion of the system. Furthermore, the local high temperature increases the temperature difference of the battery packs, which will shorten the service life of the battery packs. Therefore, thermal management is critically important to reduce the maximum temperature and the maximum temperature difference of the battery packs, which can ensure the safety and sustainable power supply for EVs and HEVs.

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Many thermal management technologies for battery packs in EVs or HEVs have been developed in the past few decades, including air cooling, liquid cooling and phase change material cooling [1]. Besides, some other components are also introduced to increase the cooling efficiency, such as heat pipes [2,3], thermoelectricity [4] and cooling plates [5–7]. Moreover, some innovative cooling technologies that couple multiple cooling methods are also developed [8–11]. Among these cooling methods, air cooling is one of the commonly used ones due to the advantages of low cost and simple structure of the system.

The performance of air-cooled system has been widely studied by many scholars. Many studies showed that the structure of the battery thermal management system (BTMS) had critical influence on thermal performance of the system. Pesaran et al. [12] designed the air-cooled system with single-wide and double-wide subsections for battery thermal management. The study indicated that the novel air flow distribution can help to deliver airflow uniformly to each battery module for uniform temperature distribution. Subsequently, Pesaran [13] investigated the system with serial ventilation cooling and parallel ventilation cooling using finite element method. The result showed that the parallel ventilation cooling system performed better than the serial one. The maximum temperature of the battery packs was reduced by 4 °C and the temperature difference was reduced by 10 °C after adopting the parallel air cooling. Mahamud et al. [14] used the reciprocating airflow for battery thermal management. The two-dimensional Computational Fluid Dynamics (CFD) model was introduced to study the performance of the system. The numerical result indicated that the reciprocating flow can reduce the temperature difference of the battery system by about 4% and the maximum cell temperature by 1.5% for a reciprocation period of 120s as compared with the uni-directional flow situation. Yu et al. [15] designed a battery thermal management system that contained both serial ventilation cooling and parallel ventilation cooling. A three-dimensional heat transfer model was developed and validated through both simulations and experiments. The results showed that the maximum temperature of the novel cooling system was reduced and the temperature uniformity was improved, compared to the one of the traditional system. Wang et al. [16] used CFD method to explore the thermal performance of battery module under different cell arrangement structures, including the rectangular arrangement, the hexagonal arrangement and the circular arrangement. The influence of the location of the fans on the thermal performance was also investigated. Besides, the cooling system with U-type [17], Z-type [18] and Plum-type arrangements [19] were also explored.

The inter-cell spacing among batteries and the angles of divergence plenum and convergence plenum are also critical factors that influence the uniformity of the velocities in cooling channels, and finally determine the cell temperature difference. Yong and Mo [20] used a lumped thermal model to study the influence of the cell spacing on the performance of lithium-ion battery system. The result indicated that the cell temperature decreased as the cell spacing increased when fixing the airflow rate. Xun et al. [21] found that the influence of cell distance was more dramatic when the airflow rate was larger, and the larger cell spacing can also reduce the cell temperature difference. Park [22] improved the cooling performance by employing the tapered manifold and pressure relief ventilation without changing the layout of the existing battery packs. Zhao et al. [23] studied the influence of the ratio of spacing distance between neighbor cells and cell diameter on the cooling performance using numerical method. The result indicated that suitable value of this ratio was reduced along as the cell diameter increased. Some scholars also changed the flow field through adapting different surface types of battery [24] and adding outlet ducts [18] to enhance the cooling performance of the BTMS.

In order to improve the performance of the BTMS, some optimization approaches have been introduced to design the structure of BTMS with synthetically consideration of different structure parameters. Based on the finite element thermal analysis, Kelly et al. [25] conducted optimization and design for six sigma processes to evaluate alternatives that reduced the cell temperature difference. Mousavi et al. [26] used tubes as the medium to cool the battery packs. The diameter of the tube and the inlet velocity of airflow were optimized through genetic algorithm to increase the Number of Transfer Unit of the system. Severino et al. [27] combined CFD method with Multi-Objective Particle Swarm Optimization and used it to design the cell spacing and the position of the inlet airflow. The results showed that the obtained optimized system can reduce both the maximum cell temperature and the maximum cell temperature difference by 2 °C.

The existing studies have shown that the performance of BTMS can be improved through optimizing the structure of the system. When designing the BTMS, CFD method is effective to obtain the airflow distribution. Usually, the structure of BTMS needs to be adjusted during the optimization process, and hundreds of CFD calculations should be conducted to explore the thermal performance of each system. However, CFD calculation is time consuming due to the large amount of grid cells. Therefore, the optimization of BTMS based on CFD method will cost much calculation time. Therefore, a simplified model is needed to evaluate the velocity distribution of the BTMS during the optimization procedure. Liu et al. [28] proposed the flow resistance network model for airflow calculation of BTMS. The result indicated that the airflow distribution by the proposed model agreed well with the one of CFD method. Due to the high calculation efficiency and reasonable accuracy, the flow resistance network model is expected to reduce the total time of structure optimization of BTMS.

In this paper, the structure optimization of the parallel air-cooled BTMS is conducted. The velocities in the cooling channels of the system is calculated using the flow resistance network model. The optimization is to arrange the widths of the inlet divergence plenum and the outlet convergence plenum to improve the cooling performance of the BTMS without changing the layout of the battery cells. Newton method is introduced to obtain the optimal plenum widths, with the target of minimizing the standard deviation of airflow velocities in the cooling channels. The structure optimization for the BTMS with fixed inlet flow rate and the one with fixed power consumption are both conducted. The airflows of the BTMS before and after optimization are calculated through CFD method, respectively, and the thermal performances of the two systems are compared to validate the effectiveness of the proposed method for parallel air-cooled BTMS design.

2. Models

2.1. Illustration of structure optimization of parallel air-cooled BTMS

The large battery pack consisting of $N \times M$ cuboid battery cells is used in the present study. The schematics of the battery cell and the battery pack are shown in Fig. 1. The battery pack is cooled by a three-dimensional parallel air-cooled system shown as Fig. 2. Air flows into the cooling system from the inlet and is distributed into the cooling channels (CCs) by divergence plenum (DP). Heat generated by the battery cells is removed by the air in the cooling channels. Then the air is converged by convergence plenum (CP). The spacings among adjacent battery cells are the same, denoted as d. The angles of DP and CP (θ_1 and θ_2) determine the airflow distribution in the cooling channels, finally influencing the temperature distribution of the battery pack. Usually, the total volume of the BTMS is limited due to the design of the vehicle. In the present