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Design of flow configuration for parallel air-cooled battery thermal management system with secondary vent

Sihui Hong, Xinqiang Zhang, Kai Chen *, Shuangfeng Wang *

Key Laboratory of Enhanced Heat Transfer and Energy Conservation of the Ministry of Education, School of Chemistry and Chemical Engineering, South China University of Technology, Guangzhou 510640, Guangdong, PR China

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ABSTRACT

Battery thermal management system (BTMS) is critical to dissipate the heat generated by the battery pack and guarantee the safety of the electric vehicles. Among the various battery thermal management technologies, the air cooling is one of the most commonly used solutions. In this paper, the cooling performance of the parallel air-cooled BTMS is improved through using the secondary vent. Computational fluid dynamics is introduced to calculate the flow field and the temperature field, finally evaluating the cooling performance of the BTMS. Mathematical analysis is conducted to explore the influences of the inlet air temperature and the heat generation rate on the battery cell temperature. The analysis results demonstrate that the temperature rise and the temperature difference of the battery pack are independent of the inlet air temperature, and are proportional to the heat generation rate for the situation of the constant heat generation rate. Subsequently, the influences of the position and the size of the secondary vent on the cooling performance of the BTMS are investigated through using the typical numerical cases. The results show that the position of the secondary vent strongly affects the maximum temperature and the maximum temperature difference of the battery pack. When the vent is on the convergence plenum, it is suggested to be located against the cooling channel around the battery cell with the maximum temperature. Compared to the vent located on the convergence plenum, the one against the outlet performs better. In this situation, the maximum temperature of the battery pack is reduced by 5 K or more, and the maximum temperature difference is reduced by 60% or more compared to the BTMS without vent for the situation of the constant heat generation rate. Moreover, the cooling performance of the BTMS becomes better as the size of the secondary vent increased, and similar conclusion can be obtained when the heat generation rate is unsteady.

1. Introduction

In nowadays, energy shortage and environmental pollution have become serious problems that influence human's life. Vehicle not only consumes much fuel, but is also one of the polluting sources. Therefore, electric vehicles (EVs) and hybrid electric vehicles (HEVs) have attracted worldwide attention in recent years, which are expected to relieve the energy shortage and environmental pollution problems. Lithium battery pack is the important power source of EVs and HEVs. The proper operating temperature for the lithium battery is usually between 0 °C and 40 °C [1–3]. However, when the battery pack works, the battery cells generate a large amount of heat caused by the inside chemical reaction and the Joule heat. If the heat cannot be ejected quickly, overheating and uneven temperature will occur in the battery pack, finally causing degradation or even failure of the battery cells. Therefore, battery thermal manage system (BTMS) is essential for heat dissipation of the battery pack to make sure that the battery pack works within the appropriate temperature range.

Many efforts have been made to improve the cooling performance of the BTMS. Air [4–7] and liquid [8–11] are two main cooling mediums that are pumped into the system to remove the heat generated by the battery cells. Heat pipe [12–14] and phase change material [15–18] were also introduced into the system to reduce the temperature difference of the battery pack. Considering the cost and the complexity of the system, the BTMS with only air cooling is one of the most commonly used solutions. In the air-cooled BTMS, the cooling performance of the system depends on the flow pattern of the air, and the flow pattern is strongly influenced by the structure of the system. Much research has been done to study the

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* Corresponding authors.

E-mail addresses: chenkaihb09@126.com (K. Chen), sfwang@scut.edu.cn (S. Wang).

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influence of the system structure on the cooling performance of the BTMS. Pesaran et al. [19] investigated the cooling performances of the BTMSs with the two ventilation patterns using finite element method, respectively. The results indicated that the maximum temperature and the maximum temperature difference of the battery pack for the parallel air cooling were respectively reduced by 4 °C and by 10 °C compared to the serial one. Mahamud et al. [20] introduced the reciprocating airflow to the BTMS. Compared to the uni-directional flow situation, the temperature difference of the battery pack was reduced by about 4% and the maximum cell temperature by 1.5% for a reciprocation period of 120 s. Yang et al. [21] developed a thermal model to predict the temperature difference of the battery pack. Then the model was used to explore the effects of longitudinal and transverse spacings on the cooling performance for the battery pack with the aligned and the staggered arrays. By trade-off the maximum temperature rise, the temperature difference, the power requirement and the cooling index, an appropriate solution of the cooling system was obtained for the aligned arrangement of battery pack. Zhao et al. [22] used numerical method to study the influence of the ratio of spacing distance between neighbor cells and cell diameter on the cooling performance of the BTMS. Yu et al. [23] reduced the temperature and the temperature difference of the system through combining the serial ventilation cooling with the parallel ventilation cooling. Wang et al. [3] considered various battery cell arrangement structures, including the rectangular arrangement, the hexagonal arrangement and the circular arrangement, and explored the influence of the cell arrangement structure on the cooling performance. The results indicated that the forced air cooling worked well with axisymmetric module structure. Wang also investigated the influences of the positions of the fans on the performance, finding that it is the best to locate the fan on the top of the module. Sun et al. [24] developed a decoupled three-dimensional battery pack thermal model to estimate the temperatures of the battery pack cells in the parallel air-cooled BTMS with U-type flow. The numerical results showed that the maximum temperature variation of battery pack can be improved by approximately 70% through introducing a tapered upper cooling duct. The conclusion was also confirmed by the experiment. Subsequently, Sun et al. [25] also improved the parallel air-cooled BTMS with Z-type flow through using the tapered inlet and outlet ducts. The results indicated that the maximum lumped cell temperature difference was reduced by 7.2 °C and the maximum lumped peak cell temperature of the battery pack is reduced by 6.3 °C. Then two secondary vent ducts are placed on opposite sides of major outlet duct to further reduce the maximum lumped cell temperature difference and the maximum lumped peak cell temperature. Chen et al. [26] used the flow resistance network model to calculate the velocity in the cooling channel of the parallel air-cooled BTMS, and introduced the Newton method to optimize the angles of the divergence and convergence plenums for more uniform velocities in the cooling channels. The results showed that the maximum temperature difference of the battery pack can be reduced by about 40% or more for the constant heat generation rate and by 30% or more for the unsteady heat generation rate. Subsequently, Chen et al. [27] developed an optimization strategy to optimize the cell spacings among the battery cells for cooling performance improvement, achieving a 42% reduction for the maximum temperature difference of the battery pack. Park [28] used numerical method to calculate the velocity field and the temperature field of the BTMSs with U-type flow and Z-type flow and compared the cooling performance of the two types of systems. Finally, the tapered manifold and pressure relief ventilation were employed to reduce the maximum temperature difference of the battery pack without changing the layout of the existing battery system. Zhou [29] used numerical method to study the cooling performance of the serial air-cooled BTMS and improved the performance of the system through introducing additional airflow inlet at the downstream of the system. The addition airflow inlet enhanced the heat transfer of the battery cells downstream which usually had high temperature in the serial system. The influences of the number, the position and the flow rate of the additional inlet were also investigated. Severino et al. [30] used Multi-Objective Particle Swarm Optimization to optimize the cell spacing of battery pack and the position of the inlet airflow to improve the flow pattern, achieving a 2 °C reduction for the maximum temperature and the maximum temperature difference of the battery pack.

The existing studies have shown that the cooling performance of BTMS is strongly influenced by the flow pattern in the system. Adding secondary vent is an effective way to change the local pressure and to control the flow pattern. In this paper, the secondary vent is introduced to reduce the maximum temperature and the maximum temperature difference of the battery pack in the parallel air-cooled BTMS. Computational Fluid Dynamics (CFD) method is used to calculate the flow field and the temperature field. Mathematical analysis for the governing equations is conducted to investigate the influences of the inlet air temperature and the heat generation rate on the cooling performance of the system. Typical numerical cases are conducted to study the influences of the position and the size of the secondary vent, finally giving out the suggestion of the optimal position of the secondary vent.

The remainder of the paper is organized as follows. Section 2 introduces the calculation model for cooling performance evaluation of the BTMS. Section 3 conducts the mathematical analysis of the governing equations. Section 4 discusses the influences of the position and the size of the secondary vent on the cooling performance. Section 5 presents the conclusions.

2. Models

2.1. Illustration of the parallel air-cooled BTMS

The parallel air-cooled BTMS shown as Fig. 1 is considered in the present study. The battery pack with $N \times M$ cuboid battery cells is included in the system. The battery cell and the battery pack are shown in Fig. 2. Air is pumped into the inlet duct of the BTMS and then is distributed into each cooling channel by the divergence plenum. The air removes the heat generated by the batter cell when flowing through the cooling channels. Then the air is converged at the end of each cooling channel by the convergence plenum into the outlet duct, finally getting out from the outlet. As the cell spacings among the battery cells are the same, the uniformity of the battery cell temperature depends on the uniformity of the airflow velocities in the cooling channels. When the airflow velocities are identical for all the cooling channels, the cell temperatures are identical and the cooling performance of the BTMS is expected to be best. However, the discrepancy of the pressure drops among the cooling channels leads to the discrepancy of the airflow velocities in the cooling channels. In the present study, the pressure

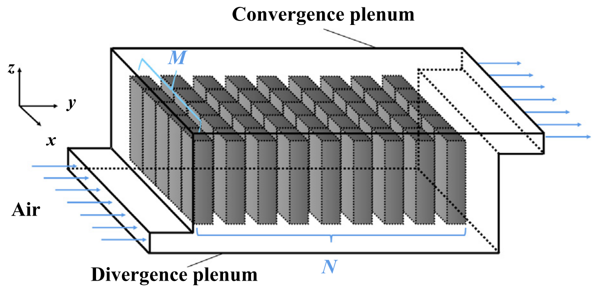

Fig. 1. Schematic of the three-dimensional parallel air-cooled BTMS [27].