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Research Paper

Thermal uniformity analysis of a hybrid battery pack using integrated phase change material, metal foam, and counterflow minichannels

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ABSTRACT

This study investigates the thermal performance and temperature uniformity of a hybrid battery thermal management system (BTMS) that integrates phase change material (PCM), metal foam, and minichannels. Computational fluid dynamics is used to model the PCM melting process and heat transfer between all components. The primary goal of the work is to investigate BTMS architectures which can enhance thermal uniformity and prevent critical temperature rise in a high-voltage battery pack under fast discharging and real-world driving cycle. Four BTMS designs are compared. The design that integrates PCM, metal foam, and counterflow minichannels is shown to have the best performance. At low pumping power (coolant Reynolds number $Re = 10$), this design reduces the peak battery temperature by 11.5 K compared to a design employing pure PCM only. This configuration also ensures a temperature difference of less than 5 K among individual battery cells, addressing thermal safety considerations and extending battery lifespan. Further analysis revealed that the inclusion of metal foam delays PCM melting, enhances both system and battery thermal uniformity, and offers a higher performance-to-weight ratio compared to designs without metal foam. Although wavy-shaped minichannels offer minimal temperature improvement (0.3 K) over straight minichannels, their higher cost and increased pumping power requirements do not justify their practicality. Under both fast discharging and real driving conditions, the first design with pure PCM provides uniform heat distribution within batteries but fails to maintain the maximum battery temperature within the optimal range. Overall, this study highlights the effectiveness of the proposed hybrid BTMS design in providing uniform temperature distribution and maintaining the maximum battery temperature within the optimal range under harsh environmental conditions, fast discharging, and the Urban Dynamometer Driving Schedule (UDDS) drive cycle.

1. Introduction

Electric vehicles (EVs) have lower operating costs, less harmful environmental impact, and zero carbon emissions during operation when compared to internal combustion engine vehicles [1]. A significant obstacle to EV utilization is the cost and complexity associated with their need for implementation with an efficient and sometimes complex battery thermal management system (BTMS). The battery maximum temperature and thermal non-uniformity are two critical factors that affect the performance of lithium-ion batteries (LIBs) and the entire battery pack [2]. Normally, the optimal operational temperature for LIBs falls within the range of 288 to 313 K. Additionally, it is recommended to maintain a maximum temperature difference of no more than 5 K within a single battery or between cells/modules [3]. When the battery experiences thermal stress beyond safe limits due to failure to maintain its optimum working temperature, there is a higher risk of battery thermal runaway, which can result in significant safety issues

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