ABSTRACT

This study presents a comprehensive investigation into the thermal behaviour and performance enhancement of air-cooled battery thermal management systems (BTMS) for lithium-ion batteries, with a focus on improving cooling effectiveness through passive geometric modifications. The work integrates literature analysis, experimental thermal characterisation, heat generation modelling, and both experimental and numerical investigations to establish a coherent framework for efficient air-cooled BTMS design.

The literature review identifies key limitations of conventional air-cooled systems, particularly their relatively low heat removal capability and poor temperature uniformity, with reported temperature differences often exceeding 5 °C in compact battery configurations. It further highlights gaps in the integration of accurate heat generation data with airflow design and the lack of experimentally validated airflow optimisation strategies.

To address these gaps, experimental characterisation of lithium-ion cells is performed to determine critical thermophysical properties. The specific heat capacity of the LFP cell is experimentally obtained in the range of approximately 900-1100 $J \cdot kg^{-1} \cdot K^{-1}$, with observable variation across different states of charge. A modified oil-bath calorimetry approach is developed to minimise heat loss, improving measurement reliability. In addition, the heat generation behaviour of the cell is analysed under different discharge rates (1C and 1.5C), showing a significant increase in temperature rise with increasing current, with peak temperature differences of the order of 6-10 °C depending on operating conditions. Based on these observations, an experimentally validated heat generation model is developed, demonstrating close agreement with measured temperature profiles, with deviations typically within ±1-2 °C.

An experimental investigation is conducted to evaluate the effect of a converging airflow passage on cooling performance. The results show that increasing airflow rate from 1.44 m^3/h to 5.76 m^3/h significantly reduces the average cell temperature, with reductions of approximately 2-3 °C observed across test cases. The introduction of a converging passage enhances local airflow velocity and convective heat transfer, resulting in improved temperature uniformity along the cell surface. The convective heat transfer coefficient is observed to increase substantially with flow rate, indicating enhanced cooling effectiveness.

A detailed numerical model is developed to analyse airflow and heat transfer at the cell level, incorporating experimentally derived thermal parameters. The model is validated against experimental data, showing good agreement with temperature deviations within ±2 °C. Numerical results indicate that the converging airflow configuration increases the local convective heat transfer coefficient by up to 20-30% compared to a uniform channel. Furthermore, the introduction of flow modifiers and optimised spacing reduces the average cell temperature and maximum temperature difference (ΔT_{max}) by up to 15-25%, depending on inlet velocity and geometric configuration.

Overall, this work demonstrates that passive geometric modifications, particularly converging airflow passages, can significantly enhance the performance of air-cooled BTMS. By establishing a strong linkage between experimental characterisation, heat generation modelling, and airflow design, the study provides practical insights for developing cost-effective and scalable thermal management solutions for lithium-ion battery systems. The findings are particularly relevant for battery energy storage applications, where simplicity, reliability, and thermal uniformity are critical design considerations.

Keywords: BTMS; Air-cooled; Lithium-ion battery; LFP; Heat generation modelling; Converging air-flow channel; Temperature uniformity.