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OPTIMISING THERMAL PERFORMANCE: A NOVEL APPROACH TO BATTERY COOLING IN ELECTRIC AND HYBRID VEHICLES

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1. ABSTRACT

The study explores thermal management strategies for Li-ion batteries crucial for Electric Vehicles and Hybrid Electric Vehicles, highlighting the challenges posed by thermal runaway and uneven temperature distribution. Active and passive cooling mechanisms are evaluated, with existing systems facing issues of weight and complexity. Addressing these limitations, a novel composite casing with variable thermal conductivity is proposed, featuring strategically placed copper pins for enhanced heat dissipation. Experimental and simulation results demonstrate the effectiveness of this approach, emphasising its potential for improving efficiency and safety in Li-ion battery systems. Overall, the study advocates for innovative thermal management solutions to meet the demands of evolving vehicle technologies.

2. INTRODUCTION

The transition to Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs) as a means to reduce reliance on fossil fuels and curb emissions has emphasised the critical role of energy storage systems, particularly lithium-ion (Li-ion) batteries. While Li-ion batteries offer advantages such as low self-discharge rates and high energy efficiency, their thermal performance presents challenges to long-term stability and safety, notably due to the risk of thermal runaway and uneven temperature distribution.

Current approaches to managing battery thermal states include active and passive cooling mechanisms. Active methods, although effective, add weight and complexity to vehicles due to the inclusion of coolant pumps and other components. Passive techniques, such as phase-changing materials (PCMs), face limitations in thermal conductivity and adaptability to varying conditions [1]. To address these limitations, this study proposes a novel composite casing for car batteries. This casing features variable thermal conductivity achieved through the strategic inclusion of carbon fibres and conductive elements like copper pins. By enhancing thermal conductivity in specific areas, the casing facilitates passive heat dissipation where it's most needed, offering a lightweight and low-maintenance thermal management solution. By integrating this composite casing into battery designs, the study aims to enhance overall efficiency and safety in EVs and HEVs, contributing to the broader transition towards sustainable transportation.

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3. METHODOLOGY

To assess different geometries of battery modules commonly used by manufacturers, a 3D model of a Li-ion battery single cell was created. Heat generation mainly occurs during charging and discharging due to changes in energy and internal resistance. To model this, an energy balance equation was formulated for a cylindrical Li-ion battery cell, considering conservation laws and heat generation using a lumped capacitance model:

$$\rho C_p \frac{\partial T}{\partial t} = hA(T - T_{amb}) + \dot{Q} \qquad (1)$$

Here, ρ is the density of active battery material (kg/m^3) and C_p is the specific heat capacity (J/kgK). T and T_{amb} denote the absolute temperature (K) and absolute temperature in ambient (K) respectively, h denotes the heat transfer coefficient (W/m^2K) and A represents the cross-sectional area of the cell (m^2). Furthermore, $\dot{Q}$ denotes the volumetric heat generation rate for the battery (W).

The model employed COMSOL Multiphysics software for Computational Fluid Dynamics (CFD) simulations of heat transfer in single cells and entire battery modules. Four module geometries (i.e. 1×24, 3×8,4×6) were evaluated, with a hexagonal arrangement of 19 cells identified as optimal for cooling and space efficiency. To validate simulation results, a custom test rig was constructed, simulating battery cells with cylindrical heating elements with the same dimensions as in the battery cells. Experiments varied spacing between elements and airflow conditions to mimic different module configurations.

For the composite casing, three manufacturing methods were considered: hand lay-up, resin infusion, and resin infusion with a caul plate. Resin infusion alone was chosen for its superior quality and surface finish. Metallic pins were strategically placed in high-temperature areas to enhance thermal conductivity. Copper pins were selected due to copper's superior thermal conductivity of 398 W/mK, making it the ideal metal for this application. These metallic pins served as thermal bridges, facilitating efficient heat transfer between the interior and exterior air of the enclosure. InfraRed thermography and K-type thermocouples were used to analyse temperature distributions and confirm the effectiveness of the metallic pins in enhancing heat transfer within the enclosure.

4. RESULTS

3D simulations were conducted for both single cells and modules with an initial temperature of 25°C, applying a convection heat transfer coefficient of 10 W/m^2K (value is taken from the calculation) and an airflow velocity of 2 m/s [2]. A square wave function represented alternating charge and discharge currents at a 7.5 C rate, with a 600-second cycle time and a relaxation period after 1500 seconds [2]. Preliminary results (refer to **Fig. 1**) indicated the maximum temperature occurred at the center core of the single cell, corresponding to the active battery material. Without airflow, single cell simulations showed a maximum temperature of 92°C, approximately 30°C higher than with 2 m/s airflow and those results were taken from the simulations.

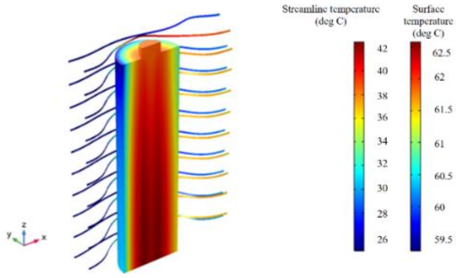

Fig. 1 Temperature distribution results of a single cell with the airflow

Experimental results, compared to simulations, were obtained from a battery module with 19 cells arranged hexagonally. The central cell, consistently showing elevated temperatures, was analysed (Refer to **Fig. 2**). During thermal imaging, enclosures were heated for a 2100-second cycle, with results captured at 1500 seconds, when maximum temperatures were reached. With pins, surface temperatures decreased significantly compared to scenarios without pins: from 47°C to 40.3°C. (Refer to **Fig. 3**)

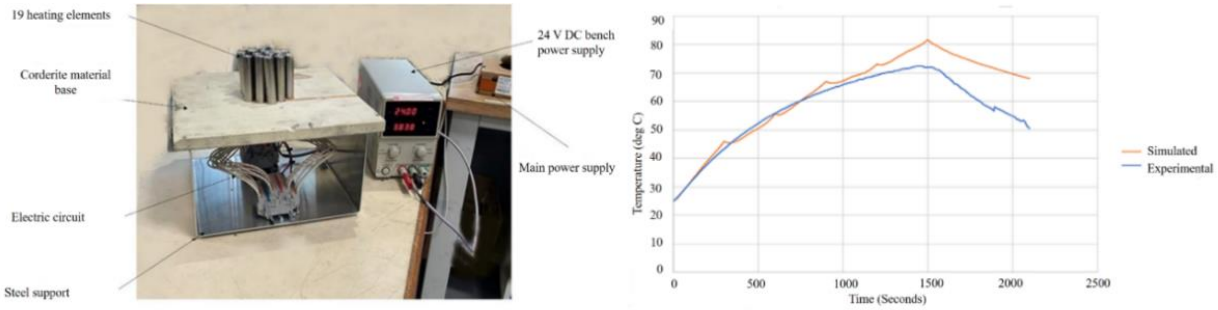

Fig. 2 Custom test rig and the comparison between experimental and simulation results for a centred cell of a battery module

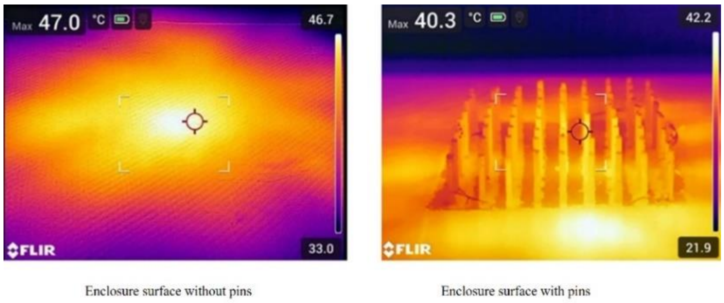

Fig. 3 IR thermography results on the enclosure without pins and with pins

5. CONCLUSIONS

In conclusion, using a modified Newman's equation with a 3D CFD model effectively simulated heat transfer in Li-ion battery cells, enhancing computational efficiency and reducing experimental data reliance. Analytical and simulation methods identified the 19-cell hexagonal arrangement as optimal for cooling and space utilisation. Experimental validation with a custom test rig matched simulation results, enabling further passive cooling exploration. Adding copper pins to the composite casing improved thermal conductivity and efficiently dissipated heat. Also, the added weight of copper pins is minimal compared to their thermal benefits, and the complexity is low compared to active cooling systems. This study highlights the importance of innovative thermal management for improving the efficiency and safety of Li-ion battery systems.

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