Comparative thermo-electrochemical investigation of cooling strategies for commercial lithium-ion cells

Lithium-ion batteries are central to the rapid development of energy storage technologies due to their superior energy density, long cycle life, and efficiency. However, understanding their thermal behaviour and optimizing cooling mechanisms remain critical for enhancing performance and ensuring operational safety, especially under high C-rates and varying ambient conditions. This thesis employs experimental and modelling approaches to investigate the thermo-electrochemical behaviour of commercial 18650 Lithium-ion cells, focusing on discharge characteristics, thermal effects, and cooling techniques.

Experiments were performed on a cylindrical cell of nominal capacity of 2.9 Ah to characterize its performance in air with ambient temperatures ranging from 25 °C to 45 °C. These studies were carried out for a range of discharge rates (1C–4C). Measurements revealed that the cell surface temperature is highly sensitive to ambient conditions. Low ambient temperatures cause a disproportionate increase in surface temperature, likely due to the low ionic conductivity of the lithium-salt-based electrolyte. The discharge capacity was observed to be higher at elevated temperatures (at 45°C), with a maximum of 10% and a minimum of 46% (at 0°C) of the rated capacity at low temperatures to the cell's rated capacity at 0.5C rate. The discharge rate primarily influenced the discharge power, while the ambient temperature had a negligible impact on average discharge power within a single discharge cycle. In contrast, the discharge energy was strongly affected by both the discharge current and the ambient temperature.

An immersion-based cooling technique using mineral oil was considered to address the thermal challenges in the cells. The use of mineral oil was considered because of its high convective heat transfer coefficient and the possibility of ensuring greater uniformity in cell temperature. Comparative analysis with natural air cooling demonstrated that immersion cooling effectively reduced temperature increase and maintained cell temperatures within the safety limit of 50 °C. However, higher flow rates of the dielectric fluid slightly reduced discharge capacity and energy, indicating a trade-off between thermal management and the electrochemical performance of lithium-ion cells.

To attain a deeper understanding of heat diffusion within the cell and subsequent advection into the dielectric liquid, a physics-based model was developed. Simulations were performed to analyze cell behaviour under varying discharge rates and cooling conditions. The model incorporated detailed information obtained from cell tear-down analyses and was validated against experimental results. Subsequently, a low-fidelity, surrogate-based, reduced-order model was trained using datasets generated from the design of experiments (DOE) sampling points. The surrogate model efficiently explored the combined effects of discharge rate, ambient temperature, inlet fluid temperature, and flow rate on performance metrics. The findings indicated that the discharge rate significantly affects polarization, narrowing the operating voltage window and reducing discharge capacity and energy. The study revealed that at least 70% of the nominal discharge capacity can be delivered under galvanostatic conditions when operating cells up to 3C rate, irrespective of the liquid flow rate. The ambient temperature primarily influenced cell temperature, discharge capacity, and energy, while its effect on discharge power was minimal.

Sensitivity analyses revealed that immersion cooling is most effective in power-intensive applications, where maintaining the cell temperature within safe limits is critical. The flow rate of the cooling fluid inversely affected discharge capacity and energy, while its impact on power output was negligible. Moreover, response surface analyses provided insights into optimal operating conditions for achieving balanced performance and safety.

This research incorporated experimental investigations, physics-based simulations, and surrogate modelling to comprehensively understand the interplay between operational parameters, thermal behaviour, and performance in lithium-ion cells. The findings contribute to developing cell cooling strategies, enabling enhanced performance and safety across diverse applications reliant on lithium-ion technology.