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Development of electro-thermal modelling of lithium-ion batteries for preventing thermal runaway

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The growing transition to clean and green energy sources has led to a rapid surge in demand of electric vehicles (EVs) powered by lithium-ion batteries (LIBs). Therefore, developing effective strategies to prevent thermal runaway and subsequent fire accidents in EVs is urgently needed. The present work develops an electro-thermal model to address the total heat generation in a LIB system due to resistance in electrodes and electrolyte along with chemical reactions taking place at electrode surface due to overheating. The energy equation considering total heat generation and heat loss, defining electro-thermal model is summarized as follows:

$$\dot{Q}_{\mathrm{total}} - \dot{Q}_{\mathrm{cooling}} = m_{\mathrm{o}} c_{\mathrm{P}} \frac{dT}{dt} \quad (1)$$

$$\dot{Q}_{\mathrm{total}} = \dot{Q}_{\mathrm{ohmic}} + \dot{Q}_{\mathrm{electrochemical}} + \dot{Q}_{\mathrm{chemical}} \quad (2)$$
$$= I^2(\mathrm{R_e}) + I^2(R_{\mathrm{ct}} + Z_{\mathrm{W}}) + m_{\mathrm{o}} \Delta H A \exp\left(\frac{-E}{R\,T}\right)$$

$$\dot{Q}_{\mathrm{cooling}} = h\, A_s (T - T_0) \quad (3)$$

Here, m_{o} is the sample mass of the cell under study, ΔH is heat of reaction (J/kg), A is pre-exponential factor (s^{-1}), E is the activation energy (J/mol), T is the sample temperature (K), and R is the universal gas constant (J/mole-K). A_S is the surface area of heat transfer (m^2), h is convective heat transfer coefficient (W/m^2K), and T_0 is the ambient temperature i.e. 298 K of the sample before testing. R_e, R_{ct}, and Z_W represent ohmic, charge-transfer, and diffusion-based resistances which result in Joule heating when current, I, is passed through the LIB system.

The LIB sample is composed of lithium iron phosphate (LFP) cathode and silicon nanocarbon as anode at 100% state of charge. The ohmic and electrochemical heat is measured using electrochemical impedance spectrometry, and the heat generation via chemical reactions is evaluated through differential scanning calorimetry technique. It is observed that electrolyte dissociation begins at around 150°C, triggering the side reactions between liquid electrolyte and the electrode surface. With increase in the temperature, gasification and cathode degradation are observed at 250°C and 391°C, respectively. Based on the sequence of events leading to thermal runaway at ~350 $^{\circ}$C, the proposed model recommends optimized cooling strategy to prevent SEI formation and cathode degradation. The cooling curve is a function of Reynolds number, as established in [1], to accurately simulate the real-world conditions for mitigating fire hazards in EVs. The results suggest a minimum cooling fan speed of 68 cm/s and 130 cm/s to prevent the formation of SEI layer and subsequently cathode degradation, respectively. The electro-thermal modelling enables optimization of the data acquisition window for real-time battery health monitoring, thereby minimizing additional costs associated with integrating impedance sensors into battery thermal management system.

References

[1] Berwal, P. et al. Combustion theory based cooling strategies for preventing thermal runaway in modern batteries. Combustion and flame. 2025;274:113995.