# Advancement in Lithium-Ion Battery Pack Thermal Modeling Based on Electrochemical Principles

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## Introduction

**Lithium-ion batteries** are widely used in electric vehicles, where energy and power demands are critical. Managing **battery packs** is challenging due to the variability in electrical and thermal interactions between cells, which can lead to thermal instability and **thermal runaway**.

This study proposes a comprehensive thermal model for the battery pack to predict cell temperatures, considering **electrochemical heat generation** due to electrochemical reactions and the interaction between the battery module and the heat exchange system.

## Modeling

**Battery packs** consist of groups of **battery modules**. Each module contains several lithium-ion batteries arranged in series, parallel, or a combination of both. Between these modules, a **heat exchange system** is implemented to effectively dissipate heat generated by each individual module. The design of the battery pack depicted in Figure 1 draws inspiration from the **Tesla Model S Battery Pack**.

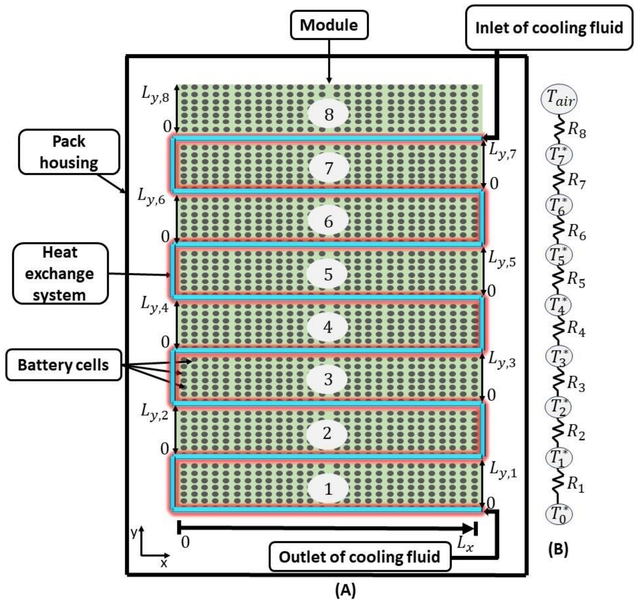


Figure 1: (A) Schematic representation of battery pack. (B) Thermal model depicting the utilization of thermal resistances for heat transfer analysis.

This study uses the heat equation to model the **thermal** distribution within each module and throughout the battery pack. The transient heat equation for each module is given by:

$$\frac{\partial T_i}{\partial t}(t,x,y) = \alpha\left(\frac{\partial^2 T_i(t,x,y)}{\partial x^2} + \frac{\partial^2 T_i(t,x,y)}{\partial y^2}\right) + Q_{\text{module}}(t,x,y),$$

where $\alpha$ is the thermal diffusivity and $Q_{\text{module}}$ is the heat generated within the module.

The boundary conditions for module 8 are expressed as:

$$T_8(t,x,L_{y,8}) = T_{\text{air}}, \quad \forall (t,x) \in (0,\infty)\times[0,L_x],$$

$$T_8(t,x,0) = T_{\text{fluid}} + \frac{q_{\text{conv,ex},i}}{2k}(l_x^2 - x^2) + \left(\frac{T_7^*}{(l_x+L_x)} - \frac{T_{\text{fluid}}}{(l_x+L_x)} - \frac{q(l_x^2-L_x^2)}{2k(l_x+L_x)}\right)(l_x+x),$$

$$T_8(t,0,y) = T_{\text{air}},$$

$$T_8(t,L_x,y) = T_{\text{air}}, \quad \forall (t,y) \in (0,\infty)\times[0,L_{y,8}].$$

For odd-numbered modules $i = 7,5,3,1$, where contact with ambient air occurs solely on the right side, the boundary conditions are as follows:

$$T_i(t,x,L_{y,i}) = T_{\text{fluid}} + \frac{q_{\text{conv,ex},i}}{2k}(l_x^2 - x^2) + \left(\frac{T_i^*}{(l_x+L_x)} - \frac{T_{\text{fluid}}}{(l_x+L_x)} - \frac{q(l_x^2-L_x^2)}{2k(l_x+L_x)}\right)(l_x+x),$$

$$T_i(t,x,0) = T_{\text{fluid}} + \frac{q_{\text{conv,ex},i}}{2k}(l_x^2 - x^2) + \left(\frac{T_{i-1}^*}{(l_x+L_x)} - \frac{T_{\text{fluid}}}{(l_x+L_x)} - \frac{q(l_x^2-L_x^2)}{2k(l_x+L_x)}\right)(l_x+x),$$

$$\forall (t,x) \in (0,\infty)\times[0,L_x],$$

$$T_i(t,0,y) = T_{\text{fluid}} + \frac{q_{\text{conv,ex},i}}{2k}(l_y^2 - y^2) + \left(\frac{T_i^*}{(l_y+L_{y,i})} - \frac{T_{\text{fluid}}}{(l_y+L_{y,i})} - \frac{q(l_y^2-L_{y,i}^2)}{2k(l_y+L_{y,i})}\right)(l_y+y),$$

$$T_i(t,L_x,y) = T_{\text{air}}, \quad \forall (t,y) \in (0,\infty)\times[0,L_{y,i}].$$

For even-numbered modules $i = 6,4,2$, where contact with ambient air is present only on the left side, the boundary conditions are as follows:

$$T_i(t,x,L_{y,i}) = T_{\text{fluid}} + \frac{q_{\text{conv,ex},i}}{2k}(l_x^2 - x^2) + \left(\frac{T_i^*}{(l_x+L_x)} - \frac{T_{\text{fluid}}}{(l_x+L_x)} - \frac{q(l_x^2-L_x^2)}{2k(l_x+L_x)}\right)(l_x+x),$$

$$T_i(t,x,0) = T_{\text{fluid}} + \frac{q_{\text{conv,ex},i}}{2k}(l_x^2 - x^2) + \left(\frac{T_{i-1}^*}{(l_x+L_x)} - \frac{T_{\text{fluid}}}{(l_x+L_x)} - \frac{q(l_x^2-L_x^2)}{2k(l_x+L_x)}\right)(l_x+x),$$

$$\forall (t,x) \in (0,\infty)\times[0,L_x],$$

$$T_i(t,0,y) = T_{\text{air}}, \quad \forall (t,y) \in (0,\infty)\times[0,L_{y,i}],$$

$$T_i(t,L_x,y) = T_{\text{fluid}} + \frac{q_{\text{conv,ex},i}}{2k}(l_x^2 - y^2) + \left(\frac{T_i^*}{(l_y+L_{y,i})} - \frac{T_{\text{fluid}}}{(l_x+L_{y,i})} - \frac{q(l_y^2-L_{y,i}^2)}{2k(l_y+L_{y,i})}\right)(l_y+x).$$

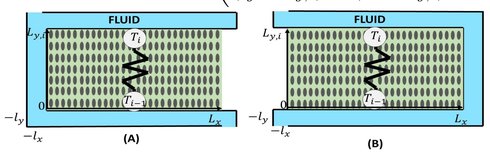


Figure 2: Module interaction with the heat exchange system to create boundary conditions. In sub-figure A, $i = 7,5,3,1$, and in sub-figure B, $i = 6,4,2$.

The heat generated in each module, $Q_{\text{module}}(t)$, is the sum of heat produced by each cell:

$$Q_{\text{module}}(t) = \frac{n \times Q_{\text{cell}}(t)}{\rho_{\text{module}} c_{p,\text{module}} V_{\text{module}}},$$

where $n$ is the number of cells, $V_{\text{module}}$ represents the module volume, and $Q_{\text{cell}}(t)$ denotes the heat generated per cell, which accounts for electrochemical reactions, conduction, and convection:

$$Q_{\text{cell}}(t) = S_{\text{cell}}(t) + q^*_{\text{cond,cell}} + q^*_{\text{conv,cell}},$$

where $S_{\text{cell}}(t)$ is the **heat from electrochemical reactions**, given by $S_{\text{cell}}(t) = I(t)V(t)$, with $I(t)$ being the current in each cell and $V(t)$ the voltage in each cell. $q^*_{\text{cond, cell}}$ represents **conduction between components**, and $q^*_{\text{conv, cell}}$ denotes the **convective heat transfer of the electrolyte**.

The **Voltage** is given by:

$$V(t) = -\frac{RT}{\alpha F}\left[\sinh^{-1}\left(\frac{1}{2c_0^+(t)a^+L^+}I(t)\right) + \sinh^{-1}\left(\frac{1}{2c_0^-(t)a^-L^-}I(t)\right)\right]$$
$$-\left(\frac{R_f^+}{a^+L^+} + \frac{R_f^-}{a^-L^-}\right)I(t) + U^+(c_{\text{ss}}^+(t),T(t)) - U^-(c_{\text{ss}}^-(t),T(t)).$$

The **electrochemical** concentrations in the electrodes are given by:

$$\frac{\partial c_s^\pm}{\partial t}(t,r_s) = \frac{1}{r_s^2}\frac{\partial}{\partial r_s}\left[D_s^\pm(T(t))r_s^2\frac{\partial c_s^\pm}{\partial r_s}(t,r_s)\right], \; t>0, \quad r_s \in (0,R_s^\pm),$$

$$\frac{\partial c_s^\pm}{\partial r_s}(t,0) = 0, \qquad \frac{\partial c_s^\pm}{\partial r_s}(t,R_s^\pm) = -\frac{1}{D_s^\pm(T(t))}j^\pm(t), \quad t>0, \qquad j^\pm(t) = \pm\frac{I(t)}{a^\pm F L^\pm}.$$

## Model Validation

This verification focused on Module 7. Figure 3 compares **ANSYS** and **MATLAB** results, showing similar heat patterns, with heat concentrated at the pack's center and dissipated at the boundaries. The maximum temperature appeared near the center, reaching 49.92°C in ANSYS and 50.80°C in MATLAB. This indicates that the thermal model effectively represents module temperature.

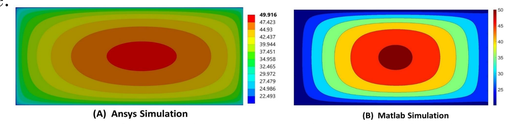


Figure 3: Comparison between Ansys simulation and Matlab simulation.

## Simulation Results

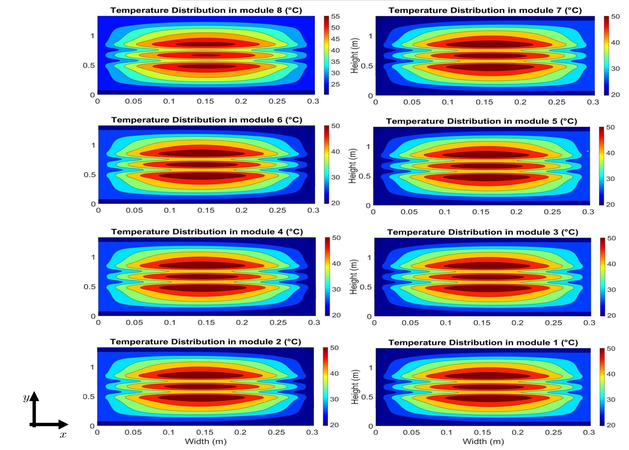


Figure 4: Thermal simulation of the eight modules.

The **finite difference method** was used in the simulation, implemented in MATLAB. The minimum temperature in all the modules stays around 20°C. Module 8 reaches a peak temperature of 55°C, while modules 1 to 7 peak at 50°C, due to differences in boundary conditions. Heat is generated at the center of each module and dissipates through the heat exchange system and air contact.

## Impact

- Uses an **electrochemical model** to determine **heat generation** within each battery due to **electrochemical reactions**, instead of using an equivalent circuit approach.
- Integrates the heat exchange system as a boundary condition for each module, capturing interactions between the battery pack and the cooling system, rather than only modeling cooling pipes.
- Disaggregates the battery pack into individual cells and modules, providing a more accurate **thermal** representation that treats the pack as a single unit.

**Reference:** Ferreira, P. & Tang, S.-X. Advancement in Lithium-Ion Battery Pack Thermal Modeling Based on Electrochemical Principles. Proceedings of the *ASME 2024 Heat Transfer Summer Conference*.