

Design of a Thermal Management System for a Lithium-ion Battery Pack

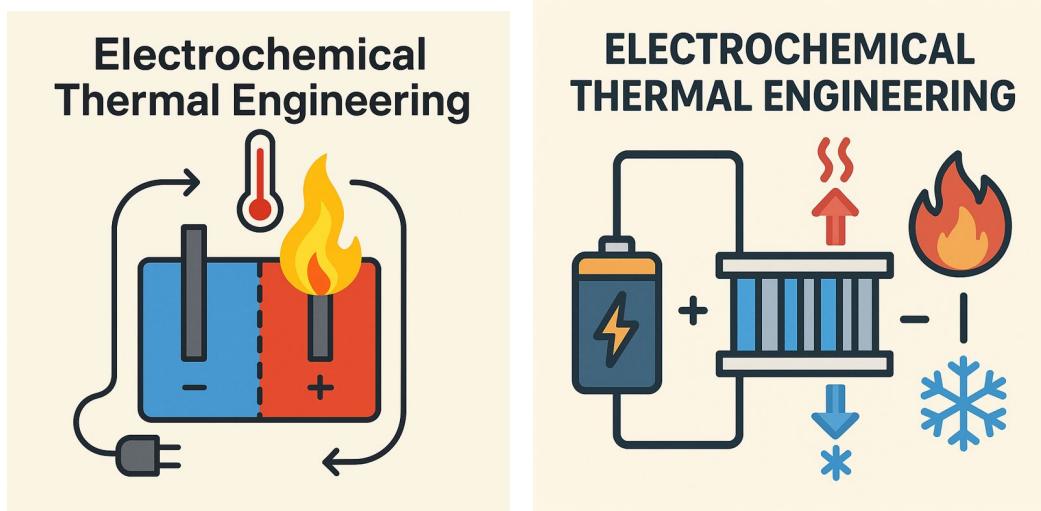
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1. Introduction to Electrochemical Thermal Engineering

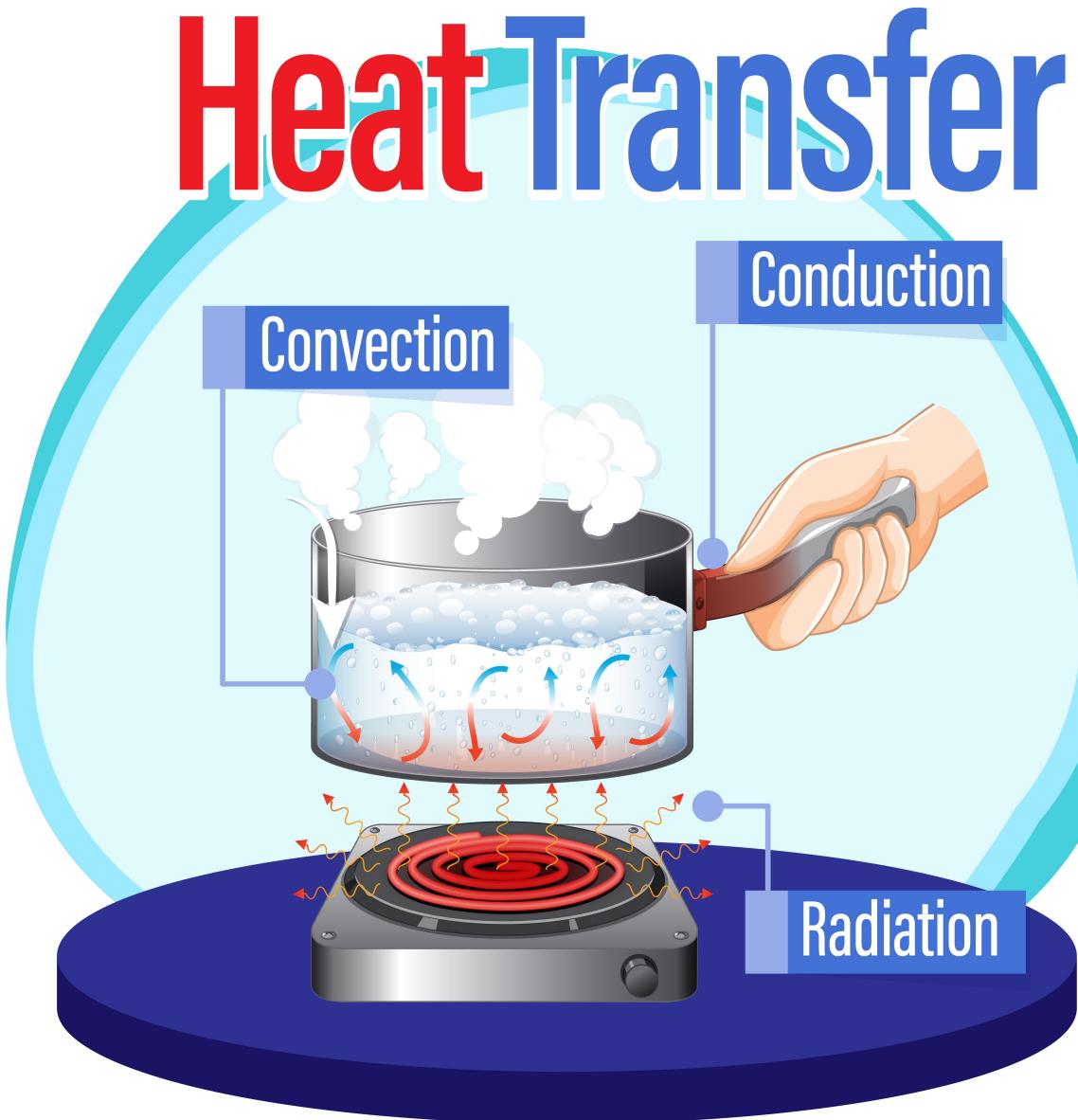


The rapid proliferation of lithium-ion (Li-ion) batteries across automotive traction, stationary energy storage, and portable electronics has necessitated a paradigm shift in thermal engineering. The battery pack, once treated as a passive energy reservoir, is now understood to be a dynamic electrochemical reactor whose performance, safety, and longevity are governed strictly by its thermal environment. The design of a Battery Thermal Management System (BTMS) is no longer a peripheral consideration of removing waste heat; it is a central architectural pillar that defines the operational envelope of the entire system.

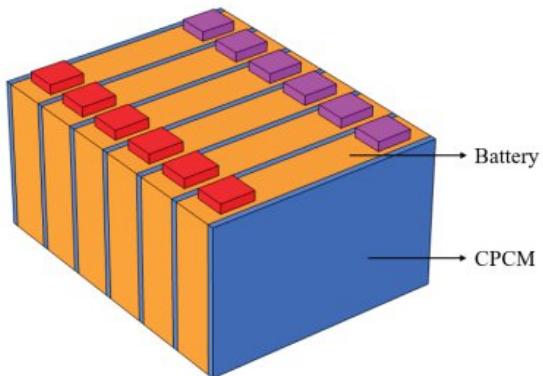
The engineering challenge is multi-dimensional. Modern Electric Vehicle (EV) requirements for extreme fast charging (XFC), which pushes currents beyond 3C or 4C, generate immense volumetric heat loads that must be rejected instantaneously to prevent localized degradation. Simultaneously, stationary storage systems deployed in harsh climates—ranging from the freezing tundras to the scorching deserts of Upper Egypt—must maintain a tight internal temperature range to ensure a twenty-year service life. This requires a nuanced understanding of heat transfer mechanisms, fluid dynamics, material science, and control theory.

This report provides an exhaustive technical analysis of the design methodologies required for high-performance BTMS. It synthesizes the underlying physics of heat generation, distinguishing between irreversible Joule heating and reversible entropic changes, and translates these into boundary conditions for mechanical design. The analysis progresses from the electrochemical cell level to the macro-system level, evaluating liquid cooling architectures, flow network optimization, and advanced control strategies such as Model Predictive Control (MPC). Furthermore, it addresses the critical safety dimension, detailing the integration of advanced thermal barriers like aerogels and mica to meet stringent propagation standards such as UL 9540A.

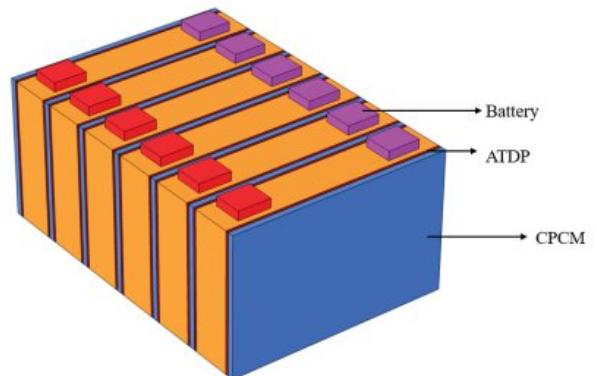
2. Thermodynamic Fundamentals and Heat Generation Mechanisms



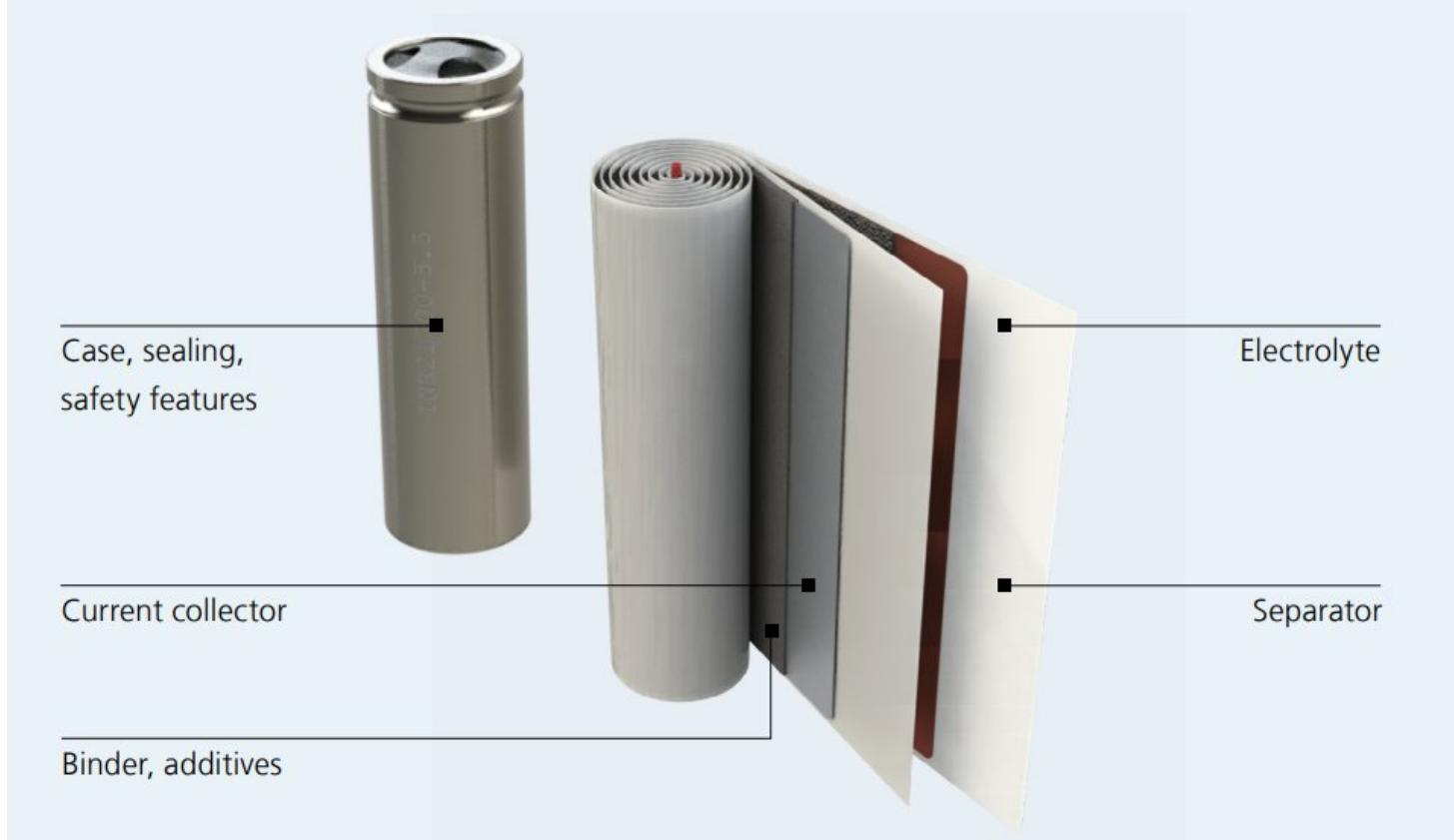
To design an effective BTMS, the engineer must first quantify the heat load with high fidelity. Heat generation in Li-ion batteries is a complex, dynamic process resulting from the coupling of electrochemical potentials, ionic transport limitations, and electrical resistances. It is insufficient to model a battery simply as a resistive heating element; a nuanced understanding of thermodynamic heat release is required to predict transient behavior accurately.

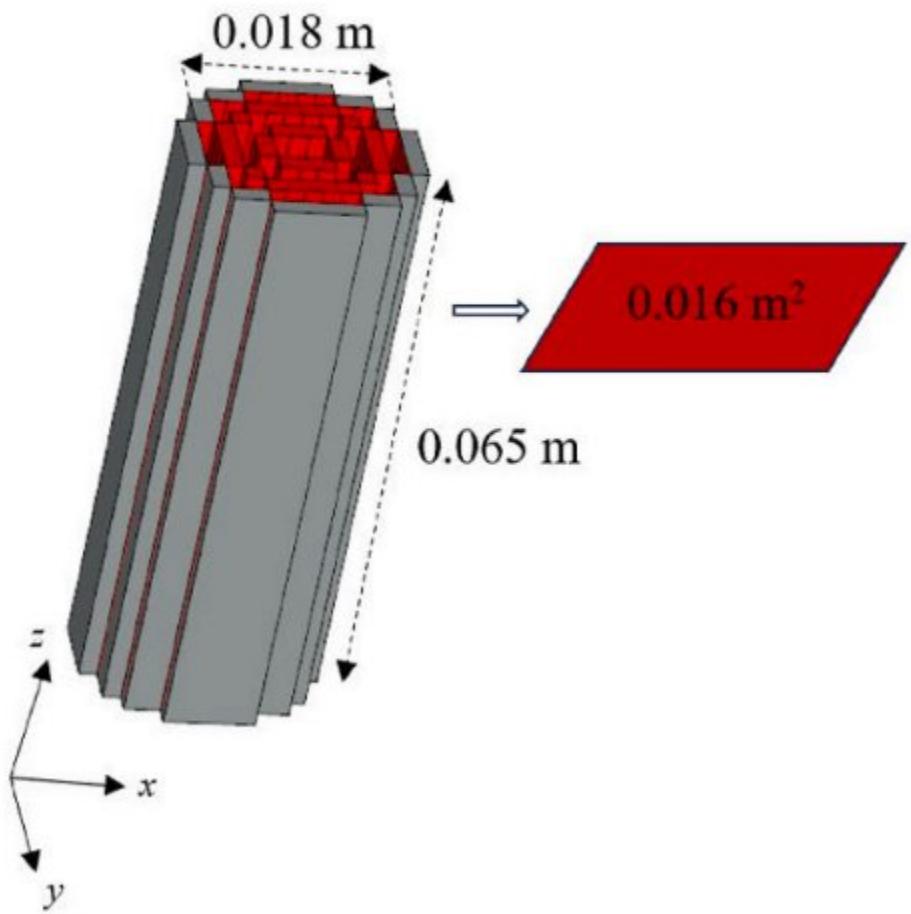


(a)



(b)





2.1. Decomposition of Heat Generation Sources

The total heat generation rate inside a battery cell, denoted as Q_{total} , is governed by the Second Law of Thermodynamics applied to electrochemical systems. It can be segmented into four primary components: irreversible heat, reversible heat, heat from side reactions, and heat of mixing.

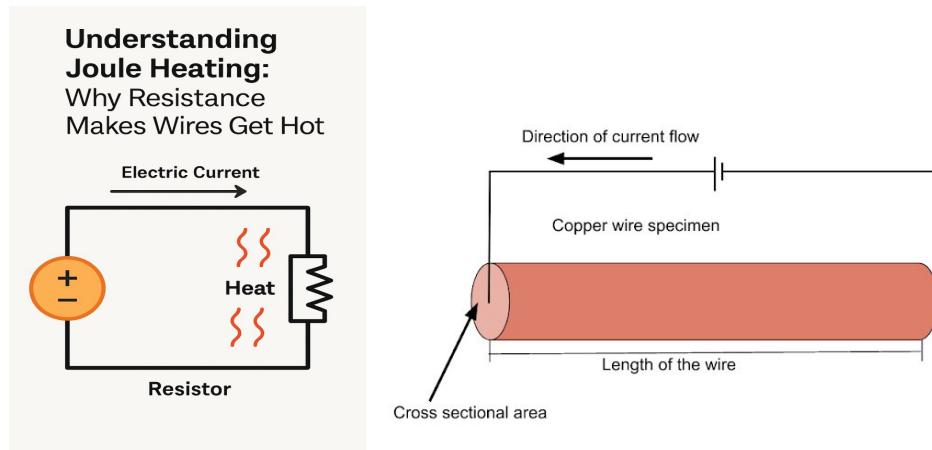
$$Q_{\text{total}} = Q_{\text{irr}} + Q_{\text{rev}} + Q_s + Q_m$$

Where:

- Q_{irr} : represents the irreversible heat, commonly known as Joule or Ohmic heating.
- Q_{rev} represents the reversible heat, arising from entropic changes in the crystal lattice.
- Q_s is the heat generated by side reactions, such as electrolyte decomposition or Solid Electrolyte Interphase (SEI) growth.
- Q_m is the heat of mixing caused by the formation and relaxation of concentration gradients within the electrolyte and active materials.

In normal operating conditions for fresh cells, the heat from side reactions (Q_s) and mixing (Q_m) is often negligible compared to the ohmic and entropic terms. However, as the cell ages or enters abuse conditions (overcharge, high temperature), Q_s becomes a dominant factor leading to thermal runaway.

2.1.1. Irreversible Heat (Joule Heating)



Irreversible heat is the result of the internal impedance of the cell opposing the flow of current. This component is strictly exothermic, meaning it releases heat regardless of whether the battery is being charged or discharged. It is physically described by the product of the current and the over-potential:

$$Q_{\text{irr}} = I(U - U_{\text{ocv}}) = I^2 R_{\text{int}}$$

Here, I is the current, U is the terminal voltage, and U_{ocv} is the open-circuit voltage. The term R_{int} represents the internal resistance, which is a composite of ohmic resistance (from electrolyte, tabs, and current collectors), charge transfer resistance at the electrode-electrolyte interface, and diffusion resistance.

Because Q_{irr} scales with the square of the current (I^2), it becomes the overwhelming driver of temperature rise during high-power applications such as fast charging or rapid acceleration. Engineering data suggests that internal resistance is not a static value; it increases significantly at low temperatures due to increased electrolyte viscosity and reduced ionic mobility, and at high temperatures due to SEI thickening.

2.1.2. Reversible Heat (Entropic Changes)

Reversible heat, often overlooked in simplified models, is associated with the entropy change (ΔS) of the electrochemical reaction as lithium ions intercalate and deintercalate from the host lattice. This term is linear with current and temperature.

$$Q_{\text{rev}} = T \Delta S \left(\frac{I}{nF} \right) = IT \frac{dE_{\text{OCV}}}{dT}$$

Where:

- T is the absolute Temperature (Kelvin)
- dE_{ocv}/dT is the entropic coefficient, representing the change in open-circuit voltage with temperature.
- n is the number of electrons transferred ($n=1$ for Li-ion intercalation).
- F is Faraday's constant (96485 C/mol).

The critical characteristic of entropic heat is its reversibility. Depending on the sign of the entropic coefficient at a specific State of Charge (SoC) and the direction of the current (charge vs. discharge), this term can be either exothermic (releasing heat) or endothermic (absorbing heat). Research indicates that at low C-rates (e.g., <0.5C), the reversible heat contribution can account for more than 50% of the total heat generated. Neglecting this term can lead to significant errors in thermal modeling, particularly for long-duration energy storage applications or during the specific SoC windows where the entropic coefficient is highly negative.

2.2. Impact of Cathode Chemistry on Thermal Signatures

The thermal behavior of a battery is heavily dictated by its electrochemistry. The choice between Lithium Iron Phosphate (LFP) and Nickel Manganese Cobalt (NMC) cathodes fundamentally alters the heat generation profile and the requirements for the BTMS.

2.2.1. Lithium Iron Phosphate (LFP) vs. Nickel Manganese Cobalt (NMC)

Comparative studies have highlighted distinct thermal differences between these leading chemistries. LFP batteries generally exhibit better thermal stability and lower self-heating rates compared to NMC.

- **Entropic Behavior:** The entropy profile of a cell varies with its crystal structure changes during lithiation. LFP cells typically show a relatively stable entropic profile with regions of endothermic behavior during discharge, which can help mitigate temperature rise. In contrast, NMC cells, particularly those with high nickel content (e.g., NMC 811), exhibit higher energy density and often display exothermic entropic behavior over a wider SoC range.
- **Heat Generation Magnitude:** Under heavy loads, NMC cells generate more heat due to their higher energy density and internal resistance characteristics relative to their capacity. Research indicates that LFP cells are approximately two times more stable during discharging at elevated temperatures (e.g., 45°C) compared to NMC.
- **Thermal Runaway Threshold:** The onset temperature for self-sustaining decomposition is significantly higher for LFP (~270°C) compared to NMC (~210°C). This influences the safety margins and the thickness of thermal barriers required in the pack design.

Parameter	Lithium Iron Phosphate (LFP)	Nickel Manganese Cobalt (NMC)	Engineering Implication
Energy Density	Lower(~160Wh/Kg)	Higher(~220-270Wh/kg)	NMC packs have higher volumetric heat density, requiring more aggressive cooling per unit volume.
Entropic Coefficient	Fluctuates; can be endothermic during discharge.	Generally exothermic; complex profile dependent on Ni content.	LFP systems may require less cooling power at low C-rates; NMC requires robust thermal management across all regimes.
Self-Discharge	Lower	Higher (~12x that of LFP)	NMC requires more careful monitoring during storage to prevent self-heating.
Voltage Stability	Flat OCV curve.	Sloped OCV curve.	LFP's stable voltage makes entropy measurement more challenging but heat generation more predictable.

2.3. Determining Heat Capacity for Transient Analysis

To translate the heat generation rate (Watts) into a temperature rise ($^{\circ}\text{C}/\text{s}$), the specific heat capacity (\mathbf{C}_p) of the cell must be accurately determined. This is a composite value representing the weighted average of the cathode, anode, separator, electrolyte, and casing materials.

The fundamental energy balance equation is:

$$\mathbf{Q} = \mathbf{m} \mathbf{C}_p \nabla \mathbf{T}$$

Where \mathbf{m} is the mass of the cell and $\nabla \mathbf{T}$ is the temperature rise.

Engineers typically determine \mathbf{C}_p using Accelerating Rate Calorimetry (ARC). In this method, a cell is placed in an adiabatic chamber, and a known amount of heat is injected (often via a heater plate or by passing a known current), while the temperature rise is monitored. Experimental values for cylindrical 18650 or 21700 cells typically fall in the range of **0.9 to 1.1 J/g·K**.¹ It is crucial to note that this value is not constant; it can vary slightly with temperature and State of Charge, although a constant average is often sufficient for preliminary sizing.

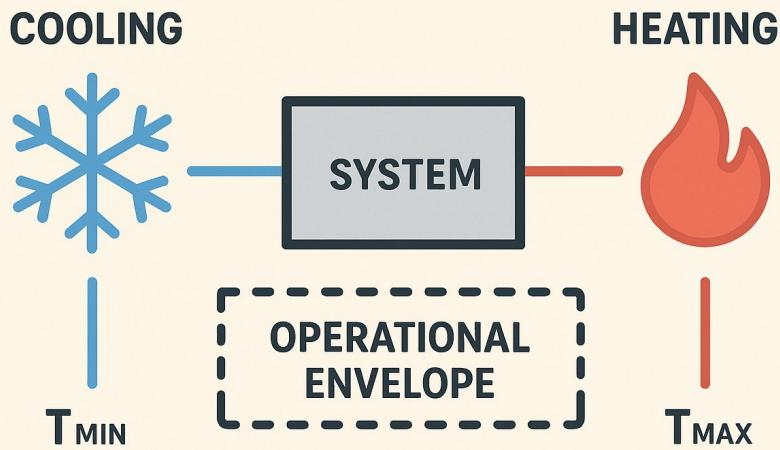
For accurate transient modeling—such as predicting the temperature spike during a 10-second acceleration boost—using the precise experimentally derived \mathbf{C}_p is essential. A 10% error in \mathbf{C}_p translates directly to a 10% error in the predicted transient temperature rise, which could lead to false positives in the Battery Management System's (BMS) derating logic.

$$\rho C_p \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(kr \frac{\partial T}{\partial r} \right) + Q_{\text{gen}} - Q_{\text{loss}}$$

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q_{\text{gen}} - hA(T - T_{\infty}) - \varepsilon \sigma A (T^4 - T_{\infty}^4)$$

3. Thermal Boundary Conditions and Operational Envelopes

THERMAL BOUNDARY CONDITIONS AND OPERATIONAL ENVELOPES



The design of the BTMS is constrained by the physicochemical limits of the battery chemistry. The "comfort zone" for a Li-ion battery is remarkably narrow, and deviations from this zone have immediate consequences for performance and safety.

3.1. Optimal Operating Temperature Range

There is a strong consensus across the industry and literature regarding the optimal thermal window for Li-ion batteries.

- **Optimal Performance:** The ideal range for operation is between **15°C and 35°C**. Within this window, the electrolyte viscosity is low enough to facilitate efficient ionic transport, while the temperature is not high enough to accelerate side reactions.
- **Target Temperature:** Most BTMS control strategies aim to maintain the average pack temperature between **20°C and 30°C**. This balance maximizes cycle life and ensures consistent power delivery.

$$Q = \frac{\Delta T}{\sum R_{\text{th}}} \quad Q = \frac{T_{\text{core}} - T_{\infty}}{R_{\text{cell}} + R_{\text{case}} + R_{\text{conv}}}$$

3.2. Constraints at Extreme Temperatures

Operating outside the optimal window triggers distinct failure mechanisms at both the high and low ends of the spectrum.

3.2.1. Low-Temperature Limits and Lithium Plating

Cold temperatures significantly increase the internal resistance of the cell due to the sluggish movement of lithium ions through the electrolyte and the solid electrolyte interphase (SEI).

- **Discharge:** Discharging is generally permissible down to -20°C, but the available capacity is severely reduced. For example, at -20°C, a cell may only deliver 60% of its nominal capacity.
- **Charging:** Charging at low temperatures is strictly limited. Below 0°C, the intercalation potential of the graphite anode drops below the potential of metallic lithium plating. Instead of entering the graphite lattice, lithium ions deposit as metallic lithium on the anode surface. This "lithium plating" is irreversible, permanently reduces capacity, and can form dendrites that may eventually pierce the separator and cause internal short circuits. Therefore, the BTMS must include a heating circuit to pre-condition the battery above freezing before fast charging can commence.

3.2.2. High-Temperature Degradation

Operating above 45°C initiates accelerated aging mechanisms.⁴

- **Arrhenius Degradation:** Battery aging follows an Arrhenius-type relationship, where the rate of degradation reactions increases exponentially with temperature. As a rule of thumb, every 10°C increase in operating temperature above 25°C cuts the battery cycle life in half.⁵
- **SEI Decomposition:** Prolonged exposure to temperatures above 60°C causes the protective SEI layer to decompose and reform continuously, consuming active lithium inventory and increasing internal resistance
- **Safety Thresholds:** Above 80°C, the risk of thermal instability increases drastically. If the temperature reaches the onset of separator melting (typically 130°C-150°C), thermal runaway becomes imminent

3.3. Temperature Uniformity (∇T) Requirements

While maintaining the average temperature is important, minimizing the temperature difference (∇T) between cells is perhaps the most critical metric for BTMS design.

- **Target:** The industry standard for high-performance packs is a maximum ∇T of $<5^\circ\text{C}$ across the entire module or pack.¹⁵
- **Consequences of Imbalance:** Thermal imbalance leads to electrical imbalance. A cell operating at 35°C will have lower impedance and age faster than a cell at 25°C . In a series string, the capacity of the pack is limited by the weakest (most degraded) cell. In parallel strings, temperature differences cause non-uniform current sharing ("current crowding"), where the hotter, lower-resistance cell takes more current, heating up further in a positive feedback loop.

4. Architecture Selection and Comparative Technology Analysis

The selection of the cooling medium and system architecture is the foundational decision in BTMS design. This choice is driven by the specific power density (W/kg), ambient environment, and cost constraints of the application.

4.1. Air Cooling (Forced Convection)

$$q_{\text{conv}} = h (T_s - T_\infty)$$

$$Q_{\text{conv}} = \int_{A_s} q_{\text{conv}} dA \quad Q_{\text{conv}} = h A_s (T_s - T_\infty)$$

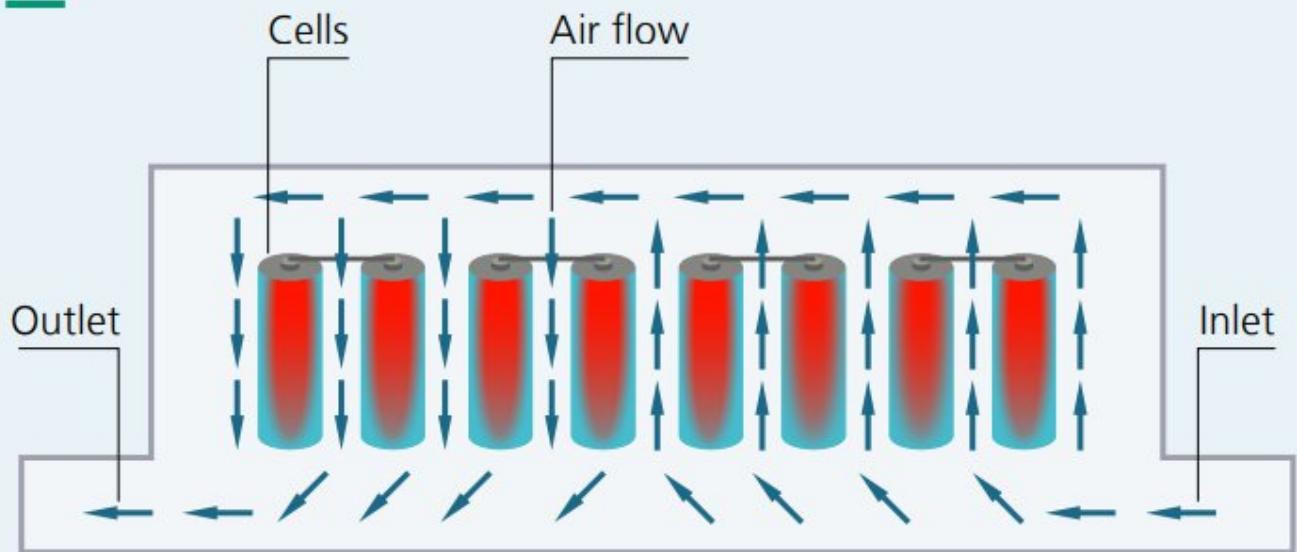
Air cooling systems circulate ambient or conditioned cabin air through the battery pack using fans.

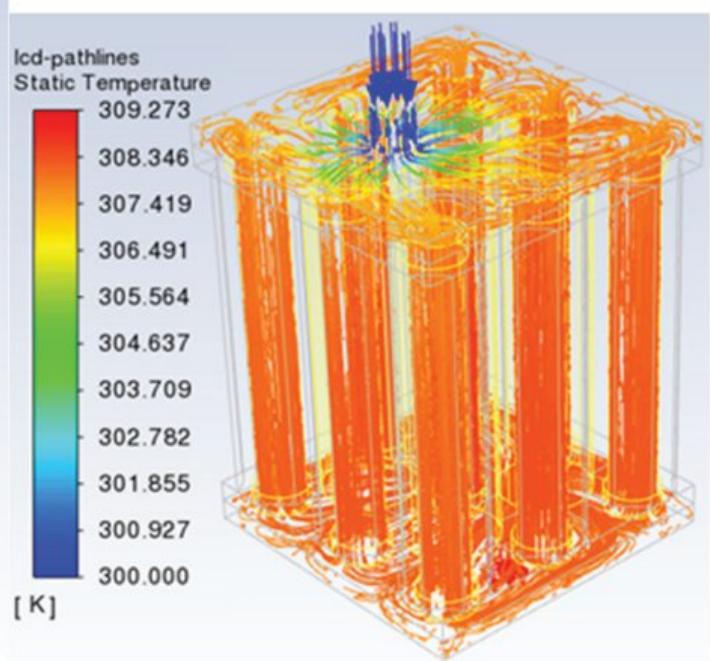
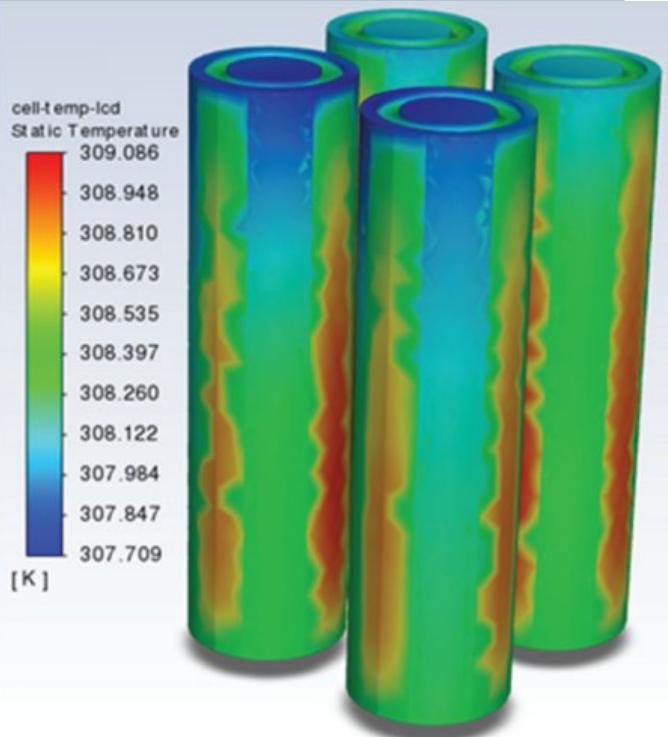
- **Mechanism:** Heat is transferred via convection from the cell surface directly to the air.
- **Advantages:** Air systems are mechanically simple, lightweight, and low cost. They eliminate the risk of coolant leakage causing electrical shorts.¹⁷
- **Limitations:** Air has very poor thermal properties compared to liquids. Its specific heat capacity ($C_p \approx 1006 \text{ J/kg}\cdot\text{K}$) and thermal conductivity ($k \approx 0.026 \text{ W/m}\cdot\text{K}$) are low. To achieve significant cooling, high volumetric flow rates are required, which leads to substantial parasitic power consumption by fans and acoustic noise issues.¹⁷ Furthermore, achieving temperature

uniformity is difficult; air heats up as it travels across the pack, naturally creating a temperature gradient from the inlet to the outlet.

- **Applicability:** Air cooling is largely restricted to Low-Speed Electric Vehicles (LSEVs), mild hybrids (HEVs), or stationary storage systems with low C-rates ($<0.5C$), where the heat generation is manageable.

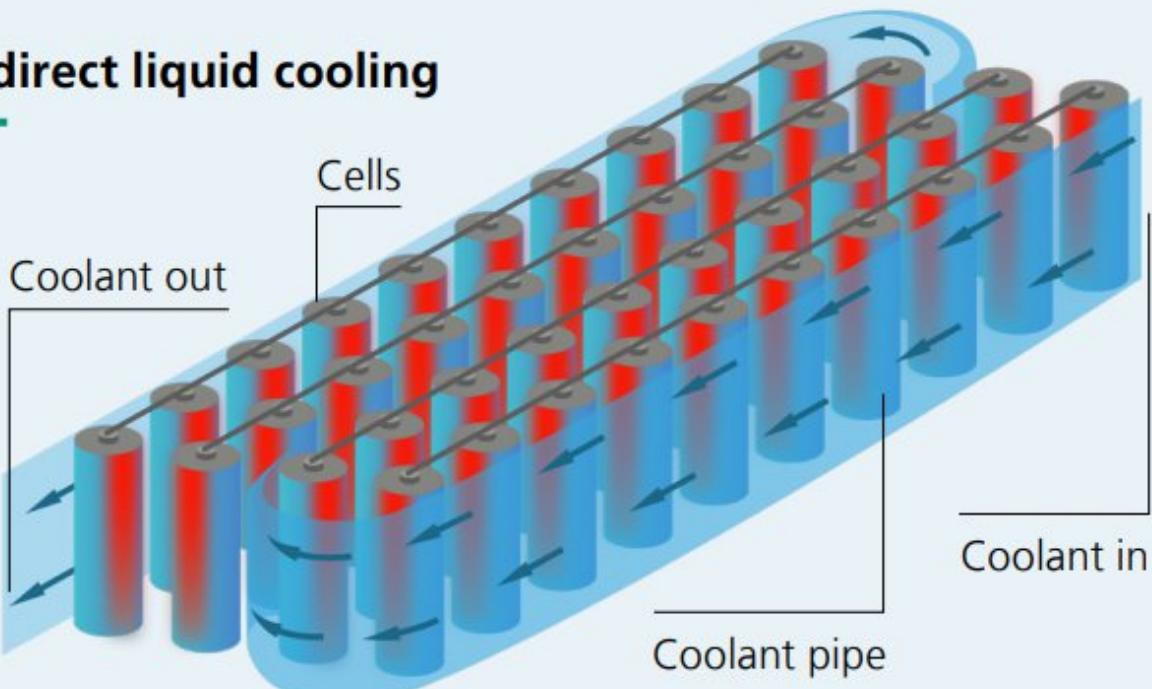
Air cooling





4.2. Indirect Liquid Cooling (Cold Plates)

Indirect liquid cooling

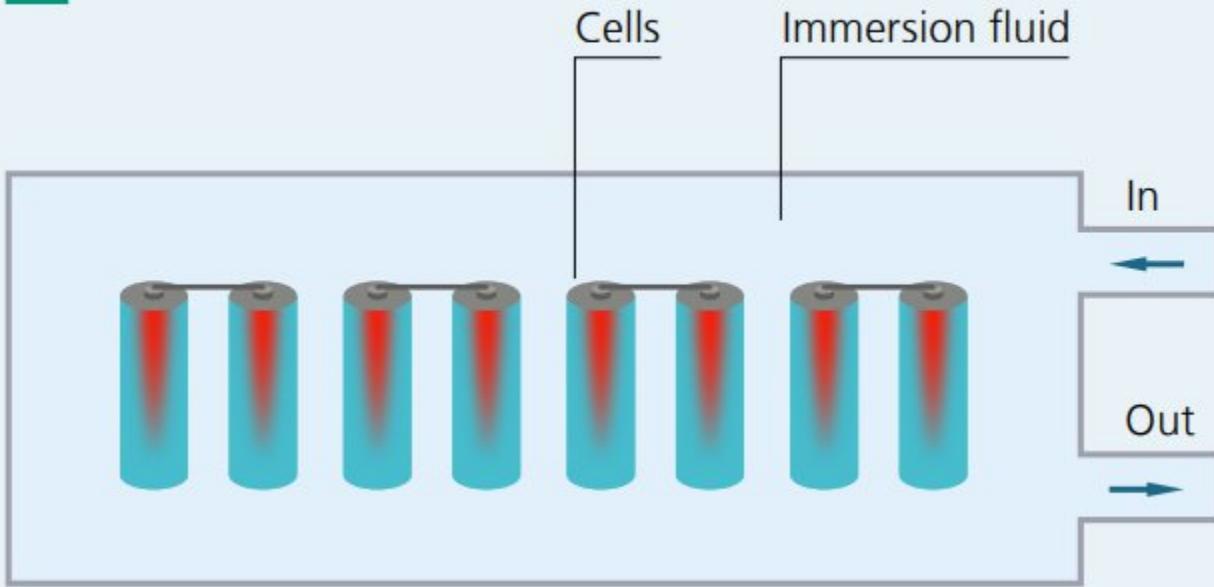


Indirect liquid cooling uses a liquid coolant (typically a 50/50 mix of water and ethylene glycol, WEG) circulating through metal channels or plates that are in thermal contact with the cells.

- **Mechanism:** Heat conducts from the cell, through a Thermal Interface Material (TIM), into the metal cold plate, and is then convected into the flowing liquid.
- **Advantages:** WEG has excellent thermal properties ($k \approx 0.4 \text{ W/m}\cdot\text{K}$) and a high heat transfer coefficient ($h \approx 1000\text{-}5000 \text{ W/m}^2\cdot\text{K}$). Liquid systems are compact and can handle the high heat fluxes associated with fast charging.²³ They allow for precise temperature control and integration with the vehicle's HVAC system (via a chiller) for sub-ambient cooling.
- **Limitations:** The system is complex, requiring pumps, radiators, reservoirs, and plumbing. The primary engineering risk is leakage, which can lead to catastrophic electrical failures. Additionally, there is a significant thermal resistance chain (Cell to TIM to Plate to Coolant) that must be minimized
- **Applicability:** This is the current industry standard for Battery Electric Vehicles (BEVs) due to its optimal balance of performance, weight, and packaging efficiency

4.3. Immersion Cooling (Direct Liquid Cooling)

Immersion cooling

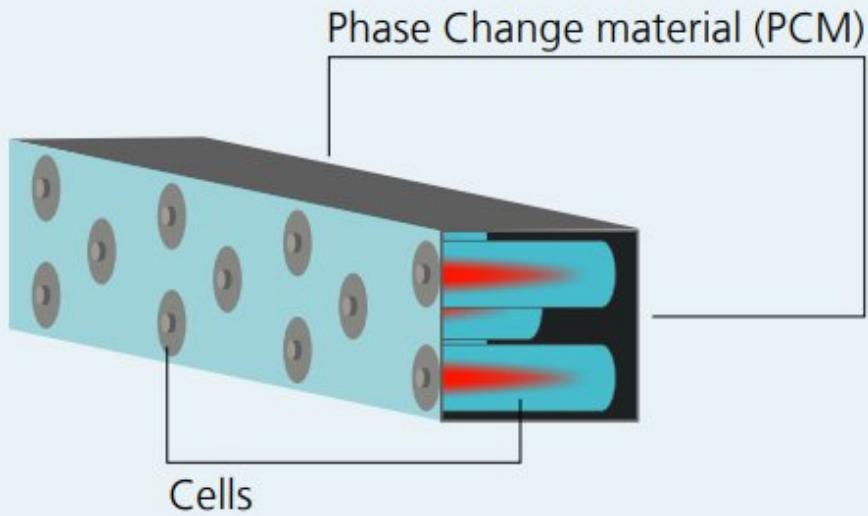


Immersion cooling involves submerging the battery cells directly into a dielectric (non-conductive) fluid.

- **Mechanism:** Heat is transferred directly from the cell surface (and often the busbars) to the fluid via convection, eliminating the contact resistance of TIMs and cold plates.
- **Advantages:** Immersion cooling offers the highest theoretical performance. Studies have shown it can reduce maximum cell temperatures by **26%** and temperature variation by **76%** compared to cold plate systems.²⁴ Because the fluid contacts the entire cell surface, uniformity is exceptional ($\nabla T \approx 1 \text{ }^{\circ}\text{C}$). The fluid also suppresses thermal runaway propagation by absorbing heat and gases from venting cells
- **Limitations:** Dielectric fluids (e.g., mineral oils, engineered fluorinated fluids) are significantly more expensive than water-glycol. They also have lower thermal conductivity and specific heat than water, meaning higher flow rates may be required, although their lower viscosity often results in lower pumping power. Material compatibility is a major challenge; the fluid must not degrade seals, adhesives, or cell packaging over the vehicle's life.
- **Applicability:** Currently reserved for high-performance applications (hypercars, motorsport) and XFC (Extreme Fast Charging) systems where heat fluxes exceed the capabilities of cold plates.

4.4. Phase Change Materials (PCM)

Phase Change Materials (PCMs)

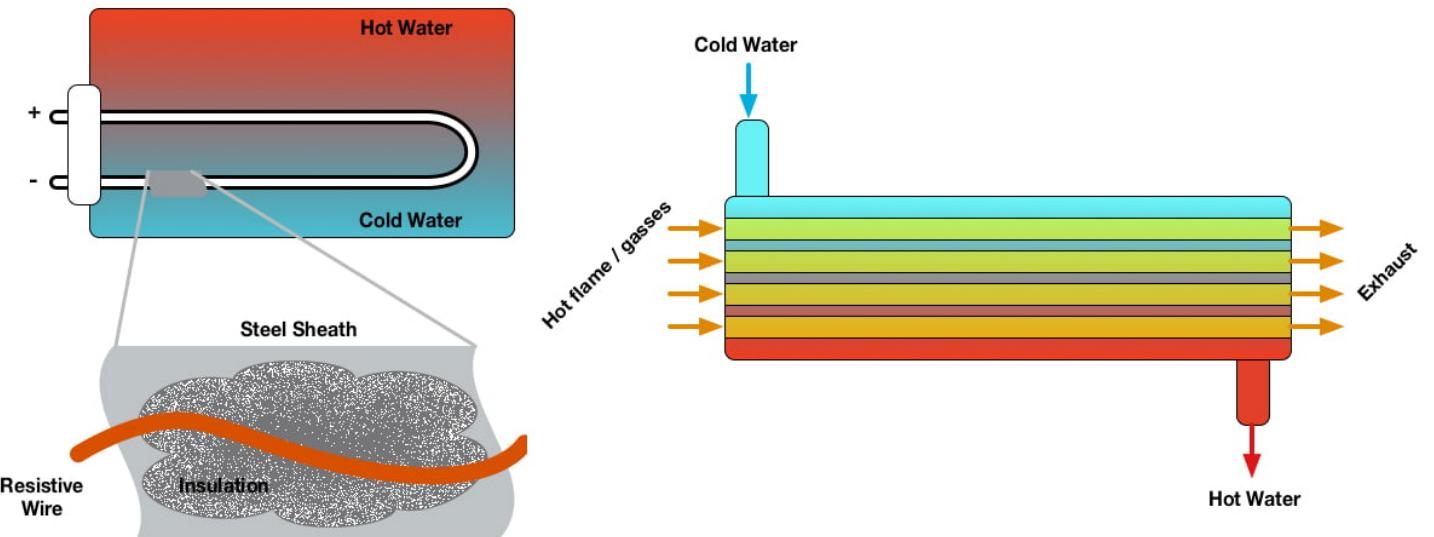


PCMs are materials that absorb and release thermal energy during the process of melting and freezing.

- **Mechanism:** As the battery heats up, the PCM melts, absorbing its latent heat of fusion at a constant temperature.
- **Advantages:** Passive operation (no pumps or fans), excellent temperature uniformity, and the ability to shave peak thermal loads.²⁸
- **Limitations:** Once the PCM is fully melted, it loses its cooling ability and often acts as a thermal insulator (low conductivity in liquid state). It requires a secondary active cooling system (e.g., air or liquid loop) to re-solidify the PCM ("recharge" the thermal buffer).²³
- **Applicability:** Often used in hybrid thermal management systems or for passive safety protection in stationary storage.

Feature	Air Cooling	Indirect Liquid (Cold Plate)	Immersion (Direct)	PCM
Cooling Medium	Air	Water-Glycol (WEG)	Dielectric Fluid	Paraffin/Hydrate
Heat Transfer Coeff (h)	20–100 W/m²K	1000–5000 W/m²K	1000–3000 W/m²K	N/A (Conduction dominated)
System Complexity	Low	High	Medium/High	Low/Medium
Leakage Risk	None	High (Conductive fluid)	Low (Dielectric fluid)	Leakage of melt
Temp Uniformity	Poor	Good	Excellent	Excellent (Transient)
Cost	Low	Medium	High	Medium

5. Engineering Liquid Cooling Systems (Cold Plates)



Given its dominance in the EV sector, the design of the liquid cooling plate is a critical engineering task. The goal is to maximize heat extraction while minimizing the pressure drop (∇P) to reduce parasitic pump power.

5.1. Channel Geometry and Flow Regimes

The internal geometry of the cold plate determines the fluid flow regime and the heat transfer efficiency.

- **Serpentine Channels:** A single continuous path that winds back and forth across the plate.
 - **Pros:** The single path ensures high fluid velocity, promoting turbulence and high heat transfer. It eliminates flow stagnation zones.
 - **Cons:** The long path length results in a very high pressure drop. There is a significant temperature gradient between the inlet and outlet, meaning the last cells in the path are cooled less effectively than the first.³¹
- **Parallel Channels:** The flow is split into multiple parallel paths.
 - **Pros:** Significantly lower pressure drop compared to serpentine. More uniform average fluid temperature across the plate.
 - **Cons:** Susceptible to flow maldistribution. Fluid will naturally take the path of least resistance. If one channel is blocked or has slightly different dimensions, flow starvation can occur, creating hot spots.³¹
- **Pin-Fin and Dimpled Structures:** Used in large-area stamped plates (e.g., pouch cell cooling). The dimples act as turbulence promoters, breaking up the thermal boundary layer and enhancing heat transfer. They also provide structural stiffness to the thin plates.²²

5.2. Hydraulic Diameter and Friction Factors

The design of the channel cross-section is governed by fluid dynamics principles. For non-circular ducts (rectangular channels in cold plates), the Reynolds number (**Re**) and friction factor (**F**) are calculated using the Hydraulic Diameter (**D_h**).

$$D_h = \frac{4A}{P} = \frac{2wh}{w+h}$$

Where **w** is the channel width and **h** is the channel height.

- **Laminar Flow (Re < 2300):** In this regime, heat transfer is diffusion-limited. The Nusselt number (**Nu**) is constant ($\approx 3.0\text{--}5.4$ depending on aspect ratio). The friction factor varies inversely with **Re** ($F = C/Re$). While pressure drop is low, heat transfer is relatively poor.
- **Turbulent Flow (Re > 4000):** In this regime, chaotic eddies mix the bulk fluid with the boundary layer, significantly increasing the heat transfer coefficient (**h**). However, the pressure drop scales with the square of the velocity ($\nabla P \propto v^2$).

Design Optimization: Engineers often use "turbulators" or surface roughness features to trip the flow into turbulence at lower Reynolds numbers, enhancing cooling without the massive pressure drop penalty of fully turbulent high-velocity flow. A recent study on circular notched fins (GV-CNF) demonstrated that optimizing fin diameter can improve the thermal performance factor by over 40% compared to standard circular fins, illustrating the potential of geometric optimization.

5.3. Manufacturing Considerations

The sealing of the cold plate is a critical reliability characteristic.

- **Brazing:** Ideally used for plates with complex internal fin structures (e.g., folded fins). It requires careful control of the brazing oven temperature profile.
- **Friction Stir Welding (FSW):** A solid-state joining process widely used for sealing the cover plate to the channel body (e.g., in aluminum extrusion designs). FSW does not melt the base material, minimizing distortion and creating a high-strength, leak-proof seal without the porosity risks associated with fusion welding.

6. Flow Network Design and Manifold Optimization

Connecting individual cold plates into a pack-level system requires a carefully designed flow network to ensure that every module receives the same cooling performance.

6.1. Series vs. Parallel Connections

- **Series Connection:** Coolant flows through Module 1, then Module 2, etc.
 - *Implication:* Module 2 receives coolant that has already picked up heat from Module 1. The last module in the chain sees the highest coolant temperature, leading to a pack-level temperature gradient. This architecture also results in a high cumulative pressure drop.³⁷
- **Parallel Connection:** Coolant is distributed from a main supply manifold to all modules simultaneously.
 - *Implication:* All modules receive coolant at the same inlet temperature (T_{in}), promoting uniformity. The pressure drop is lower.
 - *Challenge:* Flow balancing. The manifold design is critical to ensure that the pressure drop across every parallel branch is identical. If the manifold is not sized correctly, modules closer to the pump may receive more flow than those at the end.

6.2. Manifold Geometry: U-Type vs. Z-Type

The physical arrangement of the inlet and outlet manifolds has a profound effect on flow distribution in parallel systems.

- **U-Type (Reverse Return):** The coolant enters and exits the manifold system from the same side. The fluid path length for the first module is short, while the path for the last module is long.
 - *Result:* This often creates significant pressure imbalances, leading to flow starvation in the middle or end modules
- **Z-Type (Direct Return):** The coolant enters from one side and exits from the opposite side.
 - *Result:* The total path length (Supply Manifold + Module + Return Manifold) is roughly equal for every module in the system.
 - *Conclusion:* Research consistently shows that **Z-type manifolds** provide superior passive flow uniformity, minimizing the need for complex balancing valves or orifices.¹⁶ For systems where Z-type packaging is impossible, U-type manifolds can be optimized by tapering the manifold width to maintain constant fluid velocity and static pressure.

7. Thermal Interface Materials (TIMs) and Gap Fillers

The interface between the battery cell and the cooling plate is a critical bottleneck. Microscopically, surfaces are rough; when two rigid bodies touch, they only make contact at asperities (peaks), leaving air gaps in the valleys. Since air is a thermal insulator ($k \approx 0.026 \text{ W/m}\cdot\text{K}$), heat transfer is severely impeded.

7.1. Properties and Selection

TIMs are used to displace this air with a thermally conductive material ($k \approx 1.5 - 5.0 \text{ W/m}\cdot\text{K}$).

- **Thermal Conductivity vs. Compliance:** There is a fundamental trade-off. To increase conductivity, manufacturers add ceramic fillers (e.g., Alumina, Zinc Oxide). High filler loading makes the material stiffer (higher modulus). A stiff TIM cannot conform well to surface variations, creating high contact resistance. The ideal TIM is a "gap filler"—a soft, low-modulus material that can compress easily under low pressure.⁴³
- **Electrical Isolation:** In many designs (especially prismatic and pouch cells where the can may be live), the TIM must be a dielectric to prevent shorting the high-voltage battery to the grounded cooling plate. This typically necessitates silicone or urethane-based matrices.⁴³

7.2. Material Formats: Pads vs. Dispensables

- **Thermal Pads:** Pre-cut solid sheets. While easy to handle, they have a fixed thickness. If the gap tolerance varies across a large module (due to cell height variations), pads may not contact some cells or may apply excessive stress to others.
- **Disposable Gap Fillers:** These are liquid or gel-like materials dispensed by robots during assembly. They cure in place.
 - **Advantage:** They are dominating modern pack design (e.g., Cell-to-Pack) because they can accommodate large tolerance stacks without applying high stress to the cells. They also provide structural adhesion, eliminating the need for separate glues in some designs.⁴⁵

7.3. Potting Compounds

Potting involves completely encapsulating the cells and busbars in a liquid resin that cures to a solid.

- **Thermal Function:** Potting spreads heat from the cell surface to the entire volume of the module, effectively increasing the thermal mass and surface area for heat rejection. It eliminates hot spots.

- **Safety Function:** Potting provides a robust barrier against vibration, moisture, and corrosion. Crucially, it can prevent a fire in one cell from spreading by cutting off oxygen and insulating neighbors.⁴⁷
- **Weight Penalty:** Solid epoxy or urethane is heavy. Advanced "lightweight potting" materials, which incorporate hollow glass microspheres or use syntactic foams, are being developed to provide thermal conductivity with reduced density

8. Safety Engineering: Thermal Runaway and Propagation Mitigation

The ultimate design constraint for any Li-ion battery system is safety. Thermal runaway (TR) is an unstoppable exothermic chain reaction where the cell temperature rises rapidly, leading to the venting of toxic gas, fire, and explosion. The goal of the BTMS and pack design is not necessarily to prevent the *first* cell from failing (which may be caused by an internal defect), but to prevent **propagation**—ensuring that a single cell failure does not trigger a cascade that consumes the entire vehicle.

8.1. Propagation Physics and Barriers

When a cell enters TR, it releases immense heat (via conduction and convection) to its neighbors. If the neighboring cell reaches its critical onset temperature, it too will fail.

- **Thermal Barriers:** Placing insulation between cells is mandatory to break the conductive heat path.
 - **Mica:** Rigid or flexible mica sheets are the traditional solution. They are cheap, excellent dielectrics, and can withstand temperatures up to 1200°C. However, they are thermally insulating but mechanically rigid.⁵⁰
 - **Aerogels:** The state-of-the-art solution. Silica aerogels have extremely low thermal conductivity ($\approx 0.02 \text{ W/m}\cdot\text{K}$). Unlike mica, aerogel pads are compressible. They act as a "spring," accommodating the natural swelling (breathing) of pouch cells during charge cycles while maintaining their insulation properties under pressure. This dual function (mechanical compression + thermal isolation) makes them ideal for modern pouch and prismatic modules.

8.2. Venting Strategies

During TR, cells eject high-pressure gas and molten electrolyte.

- **Path Management:** The pack must feature engineered venting channels to direct this effluent away from other cells and out of the enclosure.

- **Shielding:** The gas jet from a failing cell can be hot enough to erode the casing of an adjacent cell. Mitigation strategies include using metal or high-temperature plastic plates to deflect the plume and prevent direct impingement on neighbors.

8.3. Regulatory Compliance: UL 9540A

For stationary energy storage (and increasingly relevant for EV safety benchmarking), the system must pass the **UL 9540A** test method. This rigorous standard evaluates fire propagation at four levels :

1. **Cell Level:** Determines the thermal runaway characteristics (onset temp, gas composition) of a single cell.
2. **Module Level:** Tests if TR in one cell propagates to others within the module.
3. **Unit Level:** Tests if a full rack/unit fire spreads to adjacent units.
4. **Installation Level:** Evaluates the effectiveness of fire suppression and containment in a room-scale setup.

Passing UL 9540A requires a holistic combination of the thermal barriers (aerogels), venting strategies, and spacing discussed above.

9. Control Strategies and Sensing

A robust hardware system is ineffective without intelligent control. The thermal control strategy determines when to run pumps and fans to keep the battery in the optimal window with minimal energy consumption.

9.1. Sensor Placement Optimization

It is economically and computationally impractical to place a temperature sensor on every single cell in a pack of thousands.

- **Hot Spot Identification:** Sensors should be prioritized at the thermodynamic "hot spots" of the pack—typically the geometric center of a module or the cells near the coolant outlet.
- **Observability:** Advanced techniques use Reduced Order Models (ROMs) and Partial Differential Equations (PDEs) to identify sensor locations that maximize the "observability" of the system, allowing the BMS to estimate the temperature of un-instrumented cells with high accuracy.

9.2. Control Algorithms: PID vs. MPC

- **PID (Proportional-Integral-Derivative):** The industry standard. It is a reactive controller that adjusts cooling power based on the current error (Set point minus Actual Temperature).
 - **Weakness:** It cannot "see" the future. Due to the high thermal mass of the battery, there is a delay between applying cooling and the temperature dropping. This leads to overshoot and oscillation.
- **Model Predictive Control (MPC):** A more advanced strategy that uses a mathematical model of the battery's thermal physics to *predict* future temperatures over a specific time horizon.⁶⁰

- **Mechanism:** MPC optimizes a cost function (**J**) that balances minimizing temperature deviation against minimizing energy consumption.
- **Advantage:** MPC can anticipate heat loads. For example, if the vehicle navigation knows a fast charger is 10 minutes away, MPC can pre-cool the battery to the optimal charging temperature *before* arrival. Studies indicate that MPC can reduce coolant pump power consumption by **31% to 46%** compared to PID control while maintaining tighter temperature stability.

10. System Sizing and Environmental Loads

The final design step is sizing the components (radiator, chiller, pump) to handle the worst-case thermal loads.

10.1. Calculating the Heat Load

Consider a battery pack with a peak current I and effective resistance R_{pack} .

The cooling requirement Q_{load} is the sum of internal generation and environmental heat ingress:

$$Q_{\text{load}} = (I^2 R_{\text{pack}} + Q_{\text{entropic}}) + Q_{\text{solar}} + Q_{\text{ambient}}$$

To remove this heat, the coolant flow rate \dot{m} is calculated based on the allowable coolant temperature rise (ΔT_{fluid}):

$$\dot{m} = \frac{Q_{\text{load}}}{C_{p,\text{fluid}} \cdot \Delta T_{\text{fluid}}}$$

10.2. Extreme Ambient Performance

Standard sizing often assumes a 25°C ambient. However, global automotive requirements dictate performance in environments up to **50°C** (e.g., Middle East summers).

- **Derating:** If the ambient air (50°C) is hotter than the battery limit (45°C), passive radiators are useless (heat would flow *into* the battery).
- **Active Chilling:** In these conditions, the BTMS must utilize the refrigerant circuit (chiller) to cool the coolant below ambient temperature. This places a massive load on the vehicle's AC compressor. Data shows that operating at 50°C ambient can increase the auxiliary power consumption for cooling by **6 times** compared to 25°C operation, significantly reducing vehicle range.⁶² The system must be sized to handle this parasitic load without stalling the compressor.

11. Design of Lithium Iron Battery

11.1- Data-sheet and Characteristics of Lithium Iron Battery



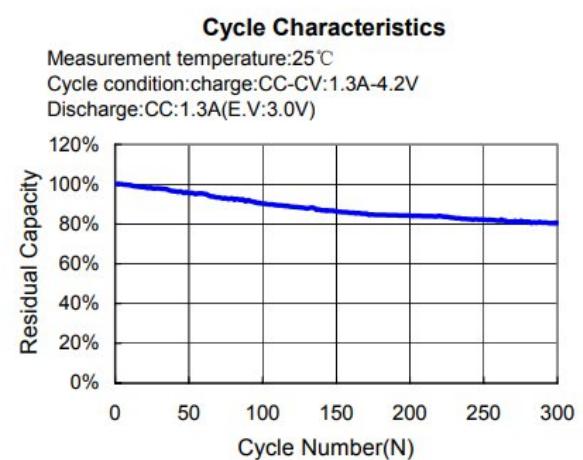
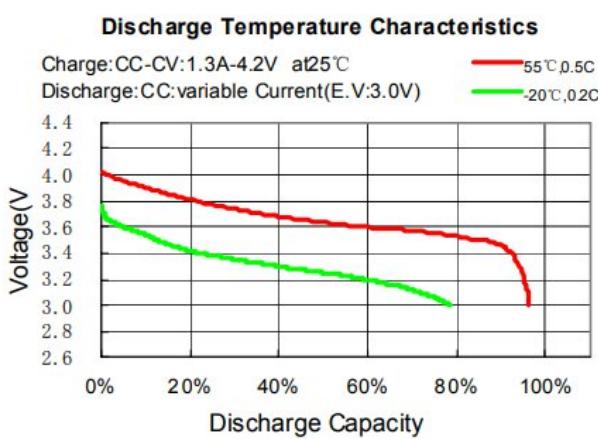
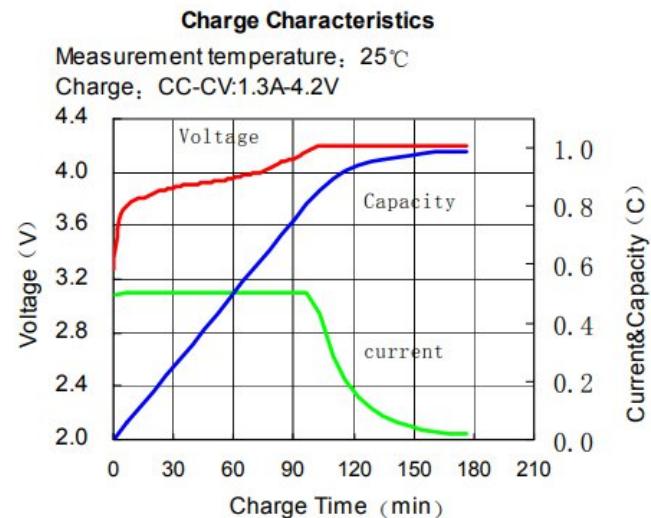
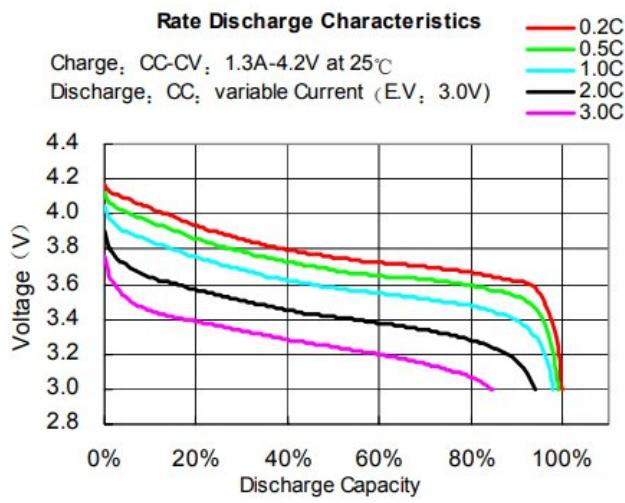
LIR18650 Datasheet

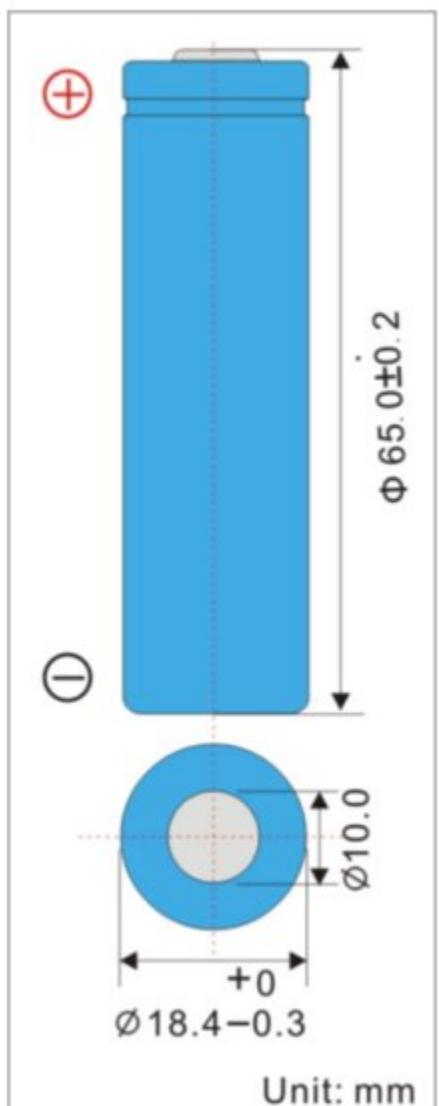
Li-ion Battery

Edition: NOV. 2010

5. BASIC CHARACTERISTICS

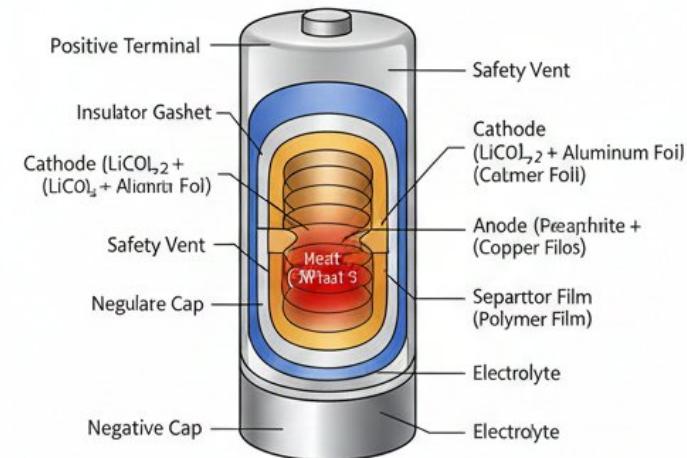
5.1 Capacity (25±5°C)	Nominal Capacity: 2600mAh (0.52A Discharge, 2.75V) Typical Capacity: 2550mAh (0.52A Discharge, 2.75V) Minimum Capacity: 2500mAh (0.52A Discharge, 2.75V)
5.2 Nominal Voltage	3.7V
5.3 Internal Impedance	≤ 70mΩ
5.4 Discharge Cut-off Voltage	3.0V
5.5 Max Charge Voltage	4.20±0.05V
5.6 Standard Charge Current	0.52A
5.7 Rapid Charge Current	1.3A
5.8 Standard Discharge Current	0.52A
5.9 Rapid Discharge Current	1.3A
5.10 Max Pulse Discharge Current	2.6A
5.11 Weight	46.5±1g
5.12 Max. Dimension	Diameter(Ø): 18.4mm Height (H): 65.2mm
5.13 Operating Temperature	Charge: 0 ~ 45°C Discharge: -20 ~ 60°C
5.14 Storage Temperature	During 1 month: -5 ~ 35°C During 6 months: 0 ~ 35°C



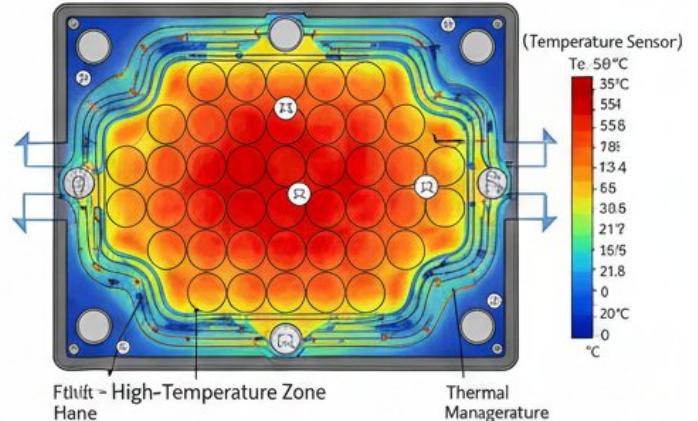


	A	B	C	D	E
1	التيار المار (I) [أمبير]	المقاومة (R) [أوم]	حرارة المقاومة (I^2R) =	ملاحظات (Rate) (Rate)	
2	0.52	0.07	0.018 W	Standard Discharge	
3	1.30	0.07	0.118 W	Rapid Discharge	
4	2.60	0.07	0.473 W	Max Pulse Discharge	
5	5.20	0.07	1.892 W	Over-load Scenario	

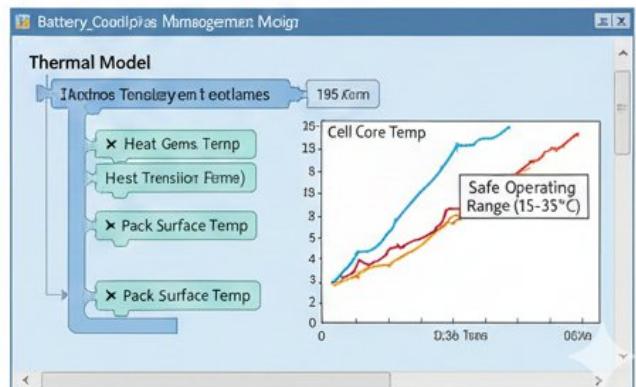
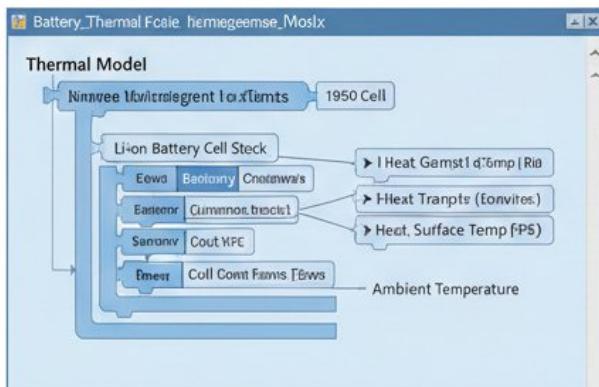
LIR18650 Cell - Internal Heat Generation



CFD Thermal Simulation - Battery Pack Under Load



Liquid Cold Plate Design - Serpentine Flow



11.2 Thermal Management System Design (Numerical Application)

For a practical design, we consider a battery pack for a light electric vehicle (e.g., an e-scooter) consisting of **100 units** of the LIR18650 cell. The cooling requirements are evaluated based on two operating scenarios:

11.2.1 Normal Operating Scenario (Rapid Discharge)

- Conditions:** Continuous discharge at 0.5C (1.3A).

- Heat Generation per Cell: 0.118W.
- Total Pack Heat Dissipation

$$Q_{\text{total}} = 11.8 \text{ watt} = 0.118 \text{ W} \times 100 \text{ Cell (Here the } A_i)$$

- **Cooling Strategy:** In this scenario, **Forced Air Cooling** may be sufficient to maintain the temperature, provided there is adequate airflow between the cells.

11.2.2 High-Stress Scenario (Pulse Discharge)

- **Conditions:** Peak power demand or pulse discharge at 1.0C (2.6A).
- **Heat Generation per Cell:** 0.473W.
- **Total Pack Heat Dissipation:**

$$Q_{\text{total}} = 100 \text{ cell} \times 0.473 \text{ W} = 47.3 \text{ watts}$$

Cooling Strategy: Under prolonged high-stress conditions, Liquid Cooling (using a cold plate with a water-glycol mixture) is recommended to prevent localized hotspots and ensure thermal uniformity.

11.3 Safety Constraints and Operating Limits

Based on the LIR18650 Datasheet, the following thermal constraints are established for the **ANSYS Fluent** and **Simulink** simulations:

11.3.1. Critical Temperature Limits

- **Maximum Discharge Temperature:** 60 °C. This is the absolute safety threshold. Exceeding this limit triggers the risk of thermal degradation or thermal runaway.
- **Maximum Charge Temperature:** 45°C. Charging at higher temperatures significantly reduces the battery's cycle life.

11.3.2. Target Operating Window (Optimization Goal)

- **Optimal Range:** 15 °C to 35 °C.
- **Goal:** The Thermal Management System (TMS) is designed to keep the pack temperature within this window to maximize electrochemical efficiency and extend the battery's lifespan (Cycle Life).

(Heating Eruation)

خليّة لينيوم أيونية سعوية 1.865 آتوم
عن معدل تفريغ ثابت داخل ترمة بفلاتي

- توليد الحرارة الداخلي (Q-gen)
- التوصيل الحراري داخل الخلية (Conduction)
- الفقد الحراري بالتحلل (Convection)
- الفرق الحراري بالإشعاع (Radiation)

$$R = 9.3 \text{ mm} = 0.0093 \text{ m}$$

$$L = 65 \text{ mm} = 0.065 \text{ m}$$

$$\rho = 2700 \text{ kg/m}^3$$

$$c_p = 900 \text{ J/kg.K}$$

$$K = 1.2 \text{ W/m.K}$$

$$I = 8 \text{ A}$$

$$V_{OC} = 3.7 \text{ V}$$

$$V = 3.3 \text{ V}$$

$$\frac{\Delta V_{OC}}{\Delta T} = 0.00015 \text{ V/K}$$

معامل الانتوبيا

$$T_{\infty} = 298 \text{ K} , h = 15 \text{ W/m}^2 \cdot \text{K}$$

$$\epsilon = 0.85 , \sigma = 5.67 \times 10^{-8}$$

Emmissivity

توزيع درجة الحرارة داخل الفلية

بمدى التكامل

$$T(r) = T_s + \frac{Q}{4K} (R^2 - r^2)$$

عند المركز ($r=0$)

وهي أقصى درجة حرارة

$$T_{max} - T_s = \frac{R^2 Q}{4K} = \frac{(0,0093)^2 \times 1.6 \times 10^5}{4 \times 1.2}$$

$$\Delta T = \frac{13,8}{4,8} = 2,88 \text{ K}$$

الفرق صغير بسب صغر نصف القطر (R)

مفيش تأثير في درجة حرارة دايم \rightarrow Steady-state

$$Q_{cond} = Q_{gen} = Q_{conv} + Q_{rad}$$

$$Q_{cond} = 2,84 \text{ W}$$

محل

حساب توليد الكهرباء الداخلية (Q_gen)

Bernardi معادلة

$$Q_{gen} = I \left[(V_{oc} - V) - T \frac{dV_{oc}}{dT} \right]$$

$$Q_{gen} = 8 \left[(3.7 - 3.3) - (298 \times 0.00015) \right]$$

$$Q_{gen} = 2.84 \text{ W}$$

Note

الحرارة عالية نسبياً لـ الفيلم ونتره \rightarrow خطأ حراري ملحوظ

Cylindrical Heat Equation

$$Q_{gen}'' + \left(\frac{\partial T}{\partial r} Kr \right) \frac{\partial}{\partial r} \frac{1}{r} = \frac{\partial T}{\partial t} \rho C_p$$

$$\hat{Q}_{gen}'' = \frac{Q_{gen}}{V} = \frac{2.84}{1.77 \times 10^{-5}} = \underline{1.6 \times 10^5 \text{ W/m}}$$

$$V = L \pi R^2 = \pi (0.0093^2 \times 0.065) \\ = 1.77 \times 10^{-5} \text{ m}^3$$

~~موقف من حيث~~

(Cylindrical Coordinat) المعادلة

$$\hat{Q}_{gen}'' + \left(\frac{\partial T}{\partial r} Kr \right) \frac{\partial}{\partial r} \frac{1}{r} = \frac{\partial T}{\partial t} \rho C_p$$

• Steady-State (أو حالات ثابتة)
حرارية

$$\frac{\partial T}{\partial t} = 0$$

$$-\frac{\hat{Q}_{gen}''}{K} = \left(\frac{\partial T}{\partial r} r \right) \frac{d}{dr} \frac{1}{r}$$

$$\frac{Q_{gen}}{K} = \frac{1.6 \times 10^5}{1.2} = \underline{1.33 \times 10^5 \text{ K/m}^2}$$

حساب درجة حرارة المقدمة (Conv + Rad)

$$Q_{gen} = Q_{conv} + Q_{rad}$$

$$2,84 = h_A (T_s - T_\infty) + \sigma A \epsilon (T_s^4 - T_\infty^4)$$

$$\frac{2,84}{0,0038} = 15 \times (T_s - 298) + 5,67 \times 10^{-8} \times 0,85 \times (T_s^4 - T_\infty^4)$$

دلالة العarde على الائمة

$$\therefore T_s = 333,4 \text{ K}$$

$$Q_{conv} = h_A (T_s - T_\infty) = 15 \times 0,0038 (333,4 - 298) \\ \approx 2,02 \text{ W}$$

$$Q_{rad} = 5,67 \times 10^{-8} \times 0,85 \times 0,0038 (333,4^4 - 298^4) \\ \approx 0,82 \text{ W}$$

$$Q_{gen} = 2,02 + 0,82 = \underline{\underline{2,84 \text{ W}}}$$

Cooling Equations:

$$(T_{core}) \\ Q = 12 \text{ W}$$

حساب درجة حرارة قلب المعايرة لشوم
تولد المعايرة حرارة معتادها
وهي مقدرة على مسائله التي يزيد
العتاداته المعايرة

$$R_{cell} = 0.6 \text{ k/W} \quad \text{مقادير المعايرة}\\ R_{case} = 0.2 \text{ k/W} \quad \text{مقادير الغلاف}\\ R_{conv} = 1.2 \text{ k/W} \quad \text{مقادير الرياح}\\ T_{\infty} = 25 {}^{\circ}\text{C} \quad \text{درجة حرارة الماء}$$

$$(T_{core})$$

الحلول
الحل

$\sum R_{th}$ حساب

$$\sum R_{th} = R_{cell} + R_{case} + R_{conv}$$

$$= 0.6 + 0.2 + 1.2 = 2.0 \text{ k/W}$$

$$(T_{core})$$

$$(Q)$$

$$Q$$

الاستهلاك قادر على الماء

$$Q = \frac{T_{core} - T_{\infty}}{R_{th}} = 12$$

$$12 = \frac{T_{core} - 25}{2.0}$$

$$T = 49 {}^{\circ}\text{C}$$

Subject :

Date :

١٤٣٥

موضوع الدرس

التاريخ

٢) معامل استهلاك الحرارة

$$R_{conn} = \frac{1}{h \cdot A_s}$$

$$A_s = \pi D L = \pi \times 0.018 \times 0.065 \approx 0.00367 \text{ m}^2$$

$$h = \frac{1}{R_{conn} \cdot A_s} = \frac{1}{4 \times 0.00367} = 68.1 \text{ W/m}^2 \cdot \text{K}$$

(Na) ← الماء حمّى سوسي

$$N_d = \frac{h \cdot D}{k_f} = \frac{68.1 \times 0.018}{0.6} = 2.043$$

Subject :

Date : / /

التاريخ موضوع الدرس

$$D = 18 \text{ mm}$$

قطر

$$L = 65 \text{ mm}$$

الطول

$$Q = 8 \text{ W}$$

حرارة تكثيف معتدلة

$$T_{\infty} = 20^{\circ}\text{C}$$

سائل المثلث يدخل ببرحة حرارة

السائل ينبع العلوي باتجاه السائل

$$k_f = 0.6 \text{ W/m.K}$$

الوحدة الحرارية

$$\rho_f = 710$$

رقم براونستول

حساب المقادير الحرارية المطلوبة
باستخدام قانون دم الحرارة

$$Q = \frac{T_s - T_{\infty}}{R_{con}}$$

$$\delta_w = \frac{40 - 20}{R_{con}}$$

$$R_{con} = 4 \text{ K/W}$$

Simulation:

1-Initial Values:

```
# =====
# 1. Define Physical Constants for 18650 Cell
# =====
# These values are typical for a commercial cell like a Panasonic NCR18650B
m = 0.0465          # Mass of the cell (kg)
Cp = 950            # Specific heat capacity (J/kg.K)
R_int = 0.045        # Internal DC resistance (Ohms) - averaged
h = 15               # Convective heat transfer coefficient (W/m^2.K)
| | | | |           # (~5-10 for still air, ~15-25 for forced air)
D = 0.018            # Diameter (m)
L = 0.065            # Length (m)
A = np.pi * D * (L + D/2) # Total Surface Area (m^2) approx. 0.0042 m^2
T_amb = 25           # Ambient temperature (°C)
T_safe = 60           # Safety limit temperature (°C)
T_runaway = 150       # Thermal runaway initiation temperature (°C)
```

```
# Electrical Properties
Q_nominal = 3.4      # Nominal capacity (Ah)
V_nominal = 3.6        # Nominal voltage (V)
V_max = 4.2           # Maximum voltage (V)
V_min = 2.5           # Minimum voltage (V)
V_cutoff = 3.0         # Cutoff voltage (V)

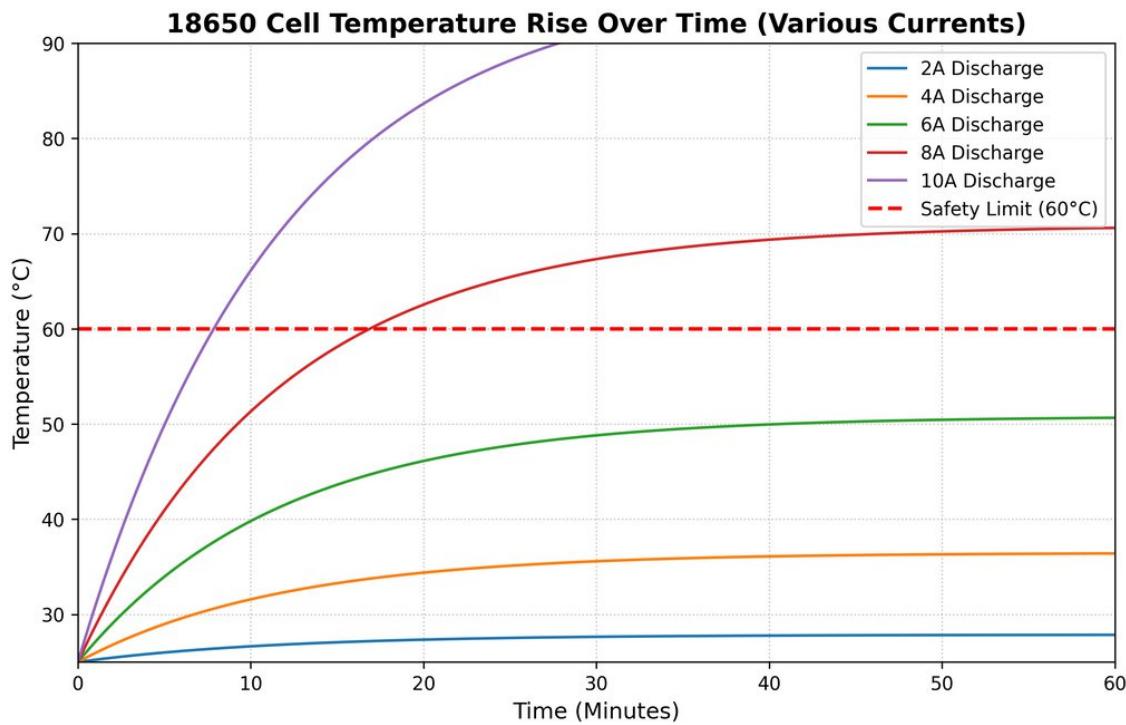
# Aging Parameters
cycle_life_nominal = 500 # Cycles to 80% capacity at 1C
fade_rate = 0.0004      # Capacity fade per cycle (0.04% per cycle)
```

Temperature Evolution & Safety Boundaries

2D Temporal Response:

At currents > 6A, the cell exceeds the 60 °C safety limit within 20 minutes.

The curves follow an exponential rise: $T(t) = T_{amb} + \Delta T_{ss} (1 - e^{-t/\tau})$.

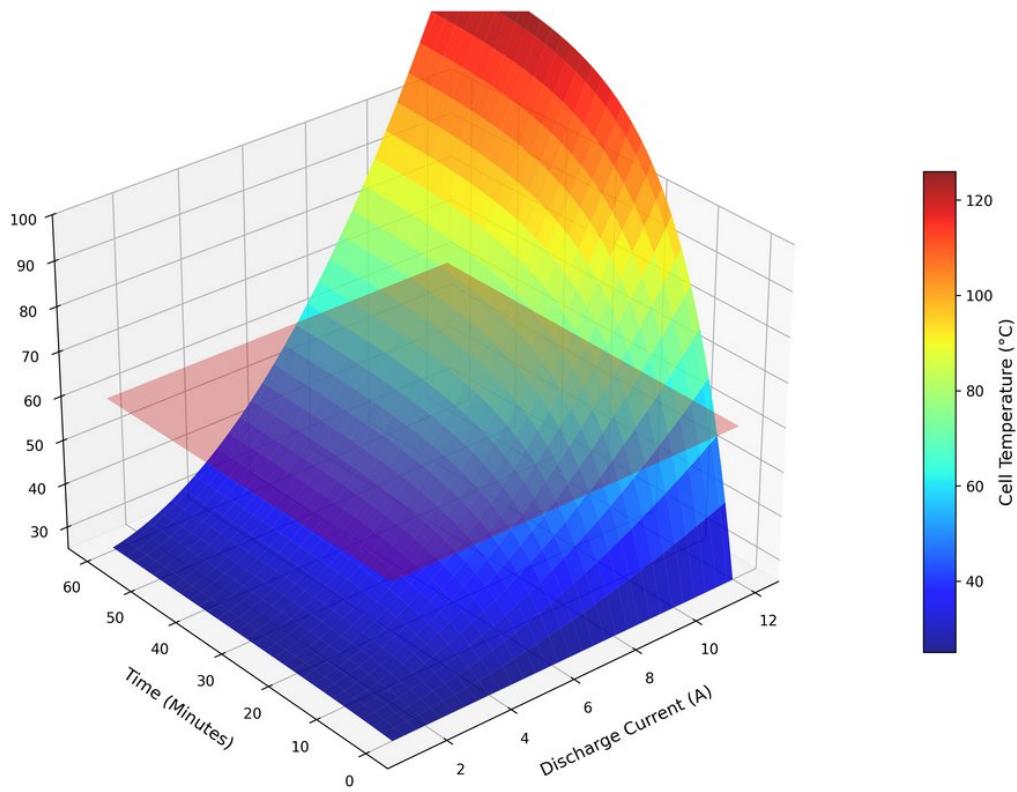


3D Thermal Envelope:

Visualizes the "Danger Zone" where Current and Time intersect.

Critical Observation: Sustained high-current discharge (> 8A) without active cooling leads to rapid thermal limit violation.

18650 Thermal Safety Envelope

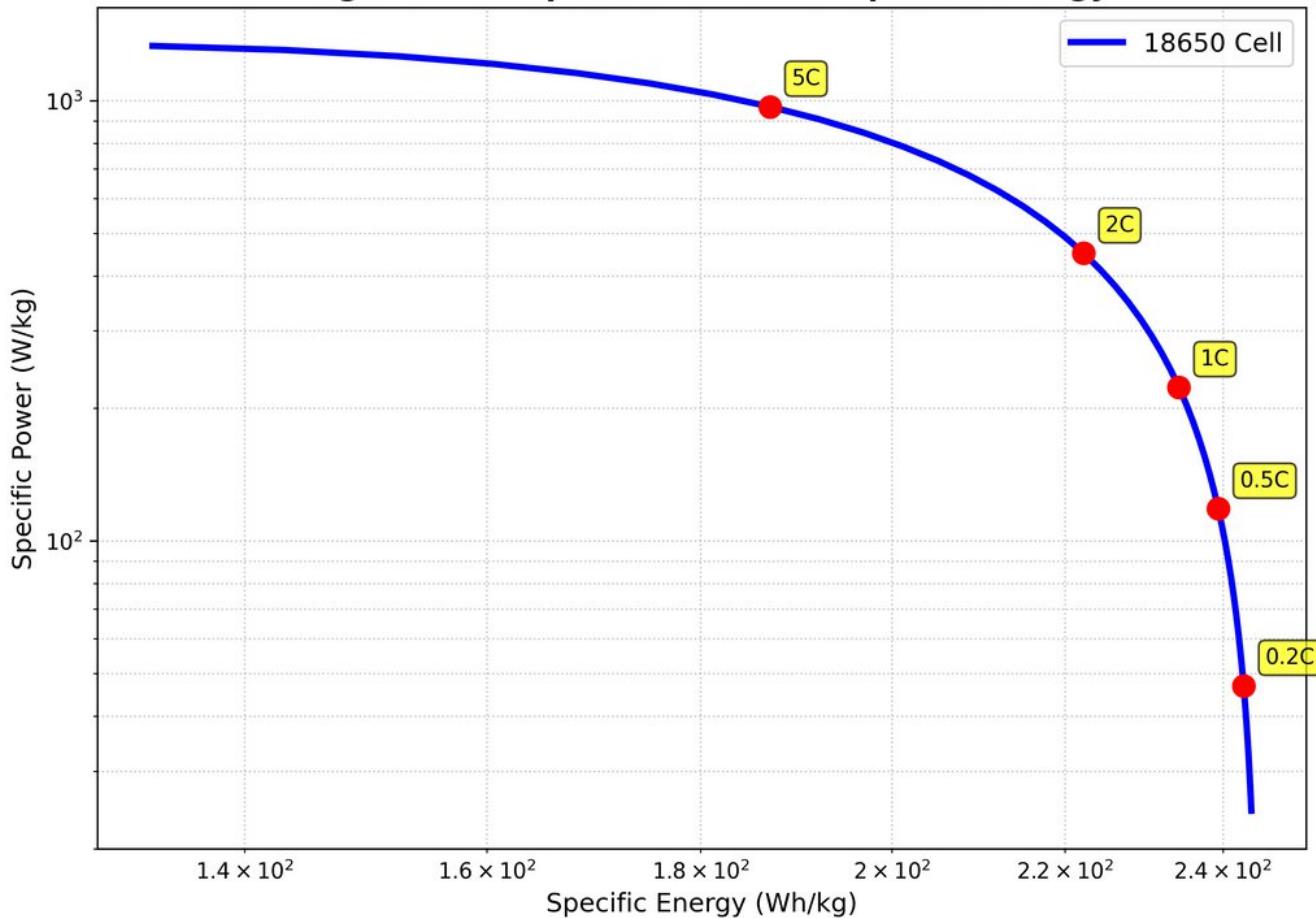


Ragone Analysis:

Demonstrates the trade-off between Specific Power (W/kg) and Specific Energy (Wh/kg).

Increased power demands lead to lower delivered energy due to thermal losses.

Ragone Plot: Specific Power vs. Specific Energy

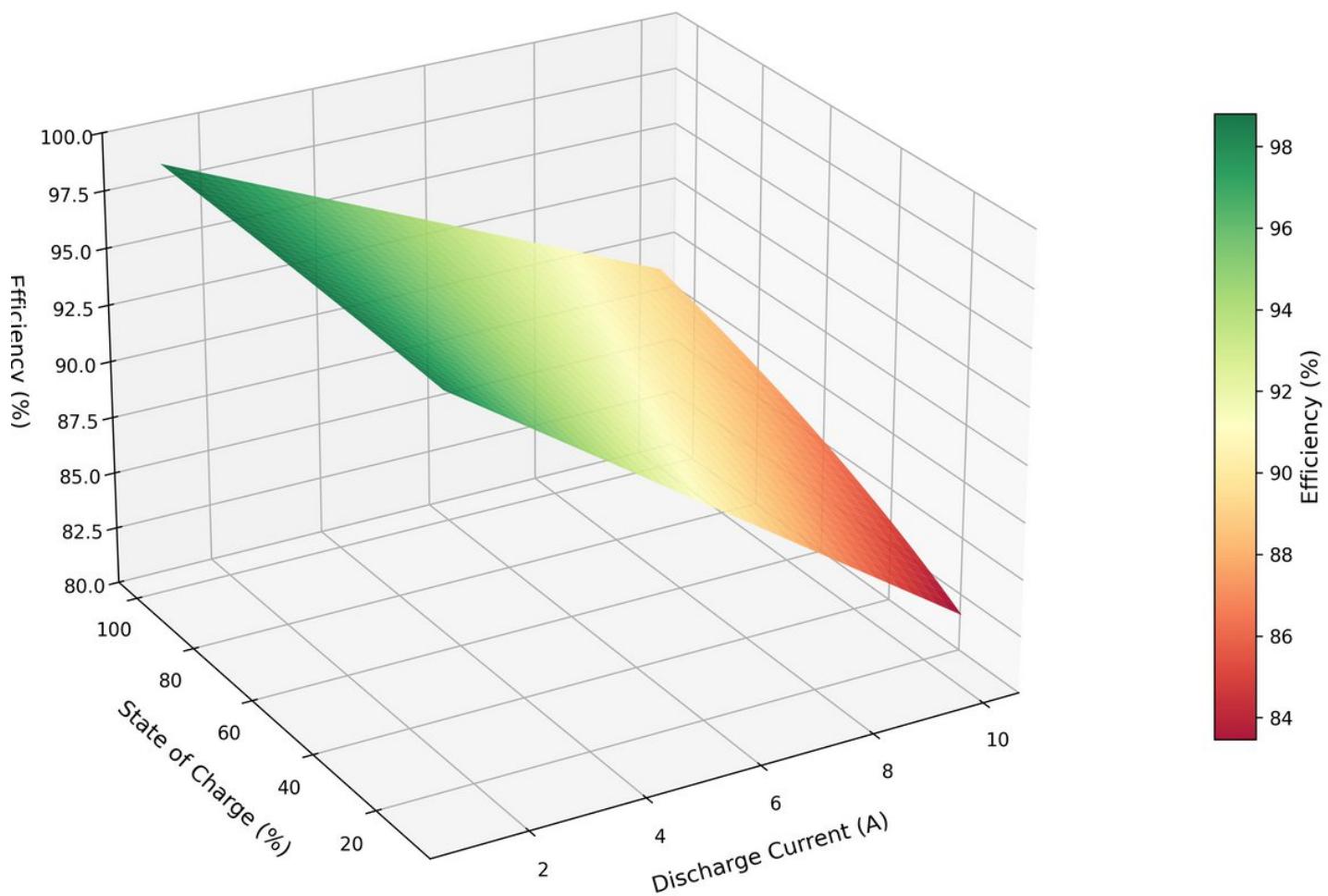


3D Efficiency Map:

Peak Efficiency: Located at low currents and high SOC (> 95%).

Efficiency Degradation: Efficiency drops below 85% during high-current bursts, as more energy is converted to waste heat rather than electrical work.

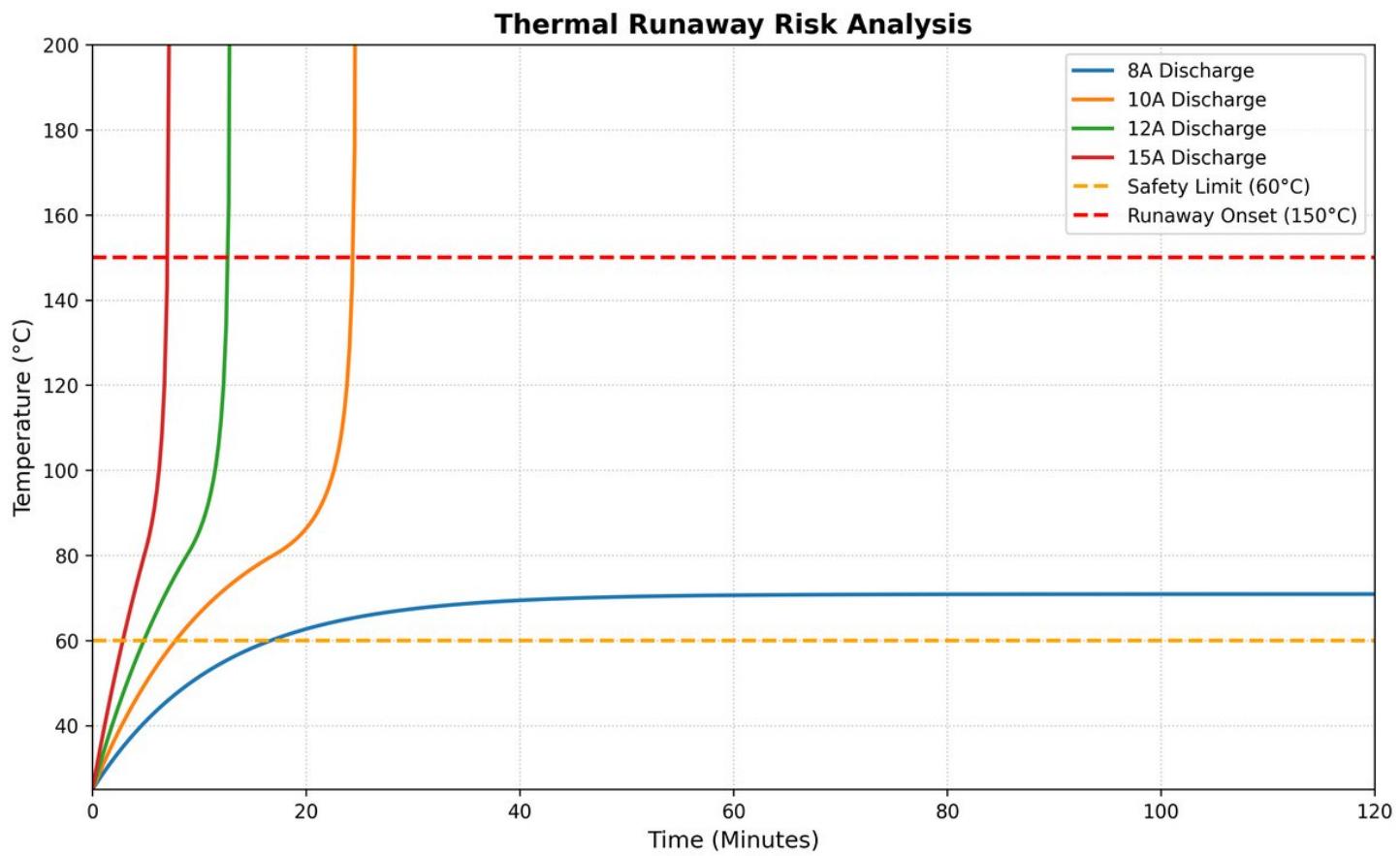
Battery Efficiency Map (Current vs. SOC)



Thermal Runaway Analysis:

Simulates the "Self-Heating" acceleration above 80°C.

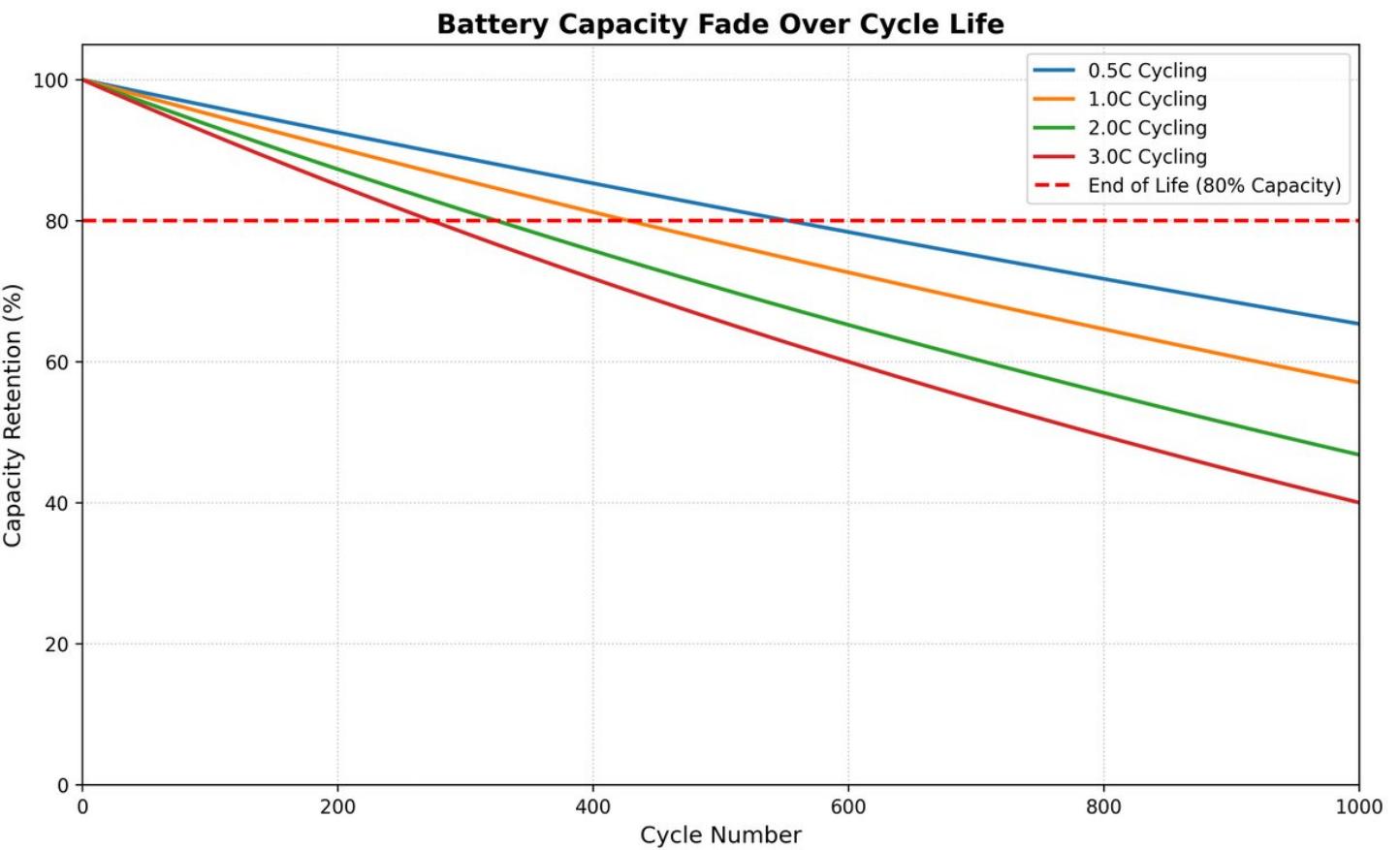
At 12A-15A, the cell reaches the Runaway Onset (150°C) rapidly, causing catastrophic failure.



Aging & Cycle Life:

Models capacity loss over 1000 cycles.

High-temperature operation significantly accelerates the Fade Rate, shortening the battery's lifespan to less than 500 cycles if not cooled properly.



Non-Uniform Temperature Profiling in 4x5 Arrays

The "Core" Effect:

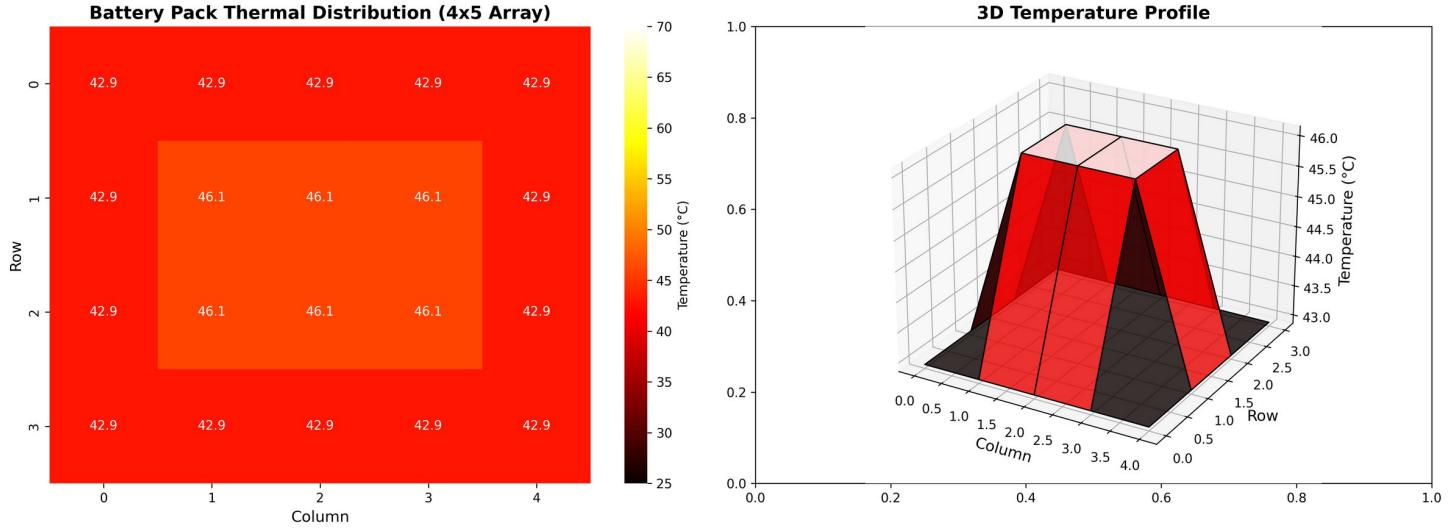
Interior cells in a pack exhibit higher temperatures compared to peripheral cells.

Cause: Reduced convective surface exposure and heat radiation from neighboring cells.

Thermal Imbalance:

A temperature delta (ΔT) of $> 5^{\circ}\text{C}$ across the pack leads to mismatched aging and electrical imbalance.

Design Conclusion: This confirms the necessity of Active Liquid Cooling or PCM to ensure pack-wide thermal uniformity.



12. Conclusion

The design of a Thermal Management System for a Lithium-ion battery pack is a complex exercise in multi-physics engineering. It requires balancing the microscopic electrochemical needs of the cell with the macroscopic constraints of vehicle packaging and environmental extremes.

- **Architecture:** **Indirect liquid cooling** remains the most balanced solution for mass-market EV applications, offering high performance and maturity. However, **immersion cooling** is emerging as the necessary solution for next-generation Extreme Fast Charging (XFC) due to its superior heat rejection and safety capabilities.
- **Optimization:** The efficiency of the liquid loop can be dramatically improved through **Z-type manifold** designs and geometric optimization of cold plate fins (e.g., circular notched fins).
- **Safety:** The integration of advanced materials such as **aerogel** thermal barriers and **dispensable gap fillers** is critical for meeting propagation standards like UL 9540A.
- **Control:** The shift from reactive PID to predictive **MPC** algorithms offers a pathway to reduce parasitic energy consumption by up to 46%, directly improving system efficiency.

Ultimately, the BTMS is the guardian of the battery. Its successful implementation ensures that the high-energy electrochemical system remains a reliable, safe, and long-lasting power source, regardless of the demands placed upon it.