

Original Research Article

Thermal management and lifetime co-optimization of lithium-ion batteries using a coupled nano-carbon/copper composite–heat-pipe cooling system

Linhui Wang^{1,2}, Ying Xu³, MOHD KHAIR HASSAN^{2*}

¹*School of Mechanical and Vehicle Engineering, Nanchang Institute of Science & Technology, Nanchang, Jiangxi, 330108, China*

²*Department of Electrical and Electronic Engineering, Faculty of Engineering, Universiti Putra Malaysia, Serdang, Selangor, 43400, Malaysia*

³*Zhejiang Institute of Communications, Hangzhou, Zhejiang, 311112, China*

Abstract: Local heat generation and weak module-level heat rejection can produce damaging hot spots in high-rate lithium-ion batteries. This study proposes a nano-carbon/copper spreader coupled to flattened heat pipes and evaluates it with a reproducible electro-thermal-aging network. A 3×4 module of 21700 NMC/graphite cells was simulated during a 900 s, 3 C discharge. Four cooling cases and 420 candidate coupled designs were compared. Relative to conventional cooling, the baseline coupled case reduced the predicted maximum temperature from 65.9 to 46.2 °C, the cell-to-cell temperature spread from 3.28 to 1.09 K, and the normalized aging index from 1.000 to 0.750. A mass-penalized compromise design reached 42.5 °C and an aging index of 0.706. The results indicate that in-plane heat spreading and remote heat rejection are complementary, while condenser conductance and interface resistance constrain their combined benefit.

Keywords: lithium-ion battery; thermal management; nano-carbon/copper; heat pipe; lifetime optimization

1. Introduction

High-rate operation raises irreversible and reversible heat generation, while restricted module surfaces limit heat rejection ^[1-2]. Local heating accelerates side reactions, and cell-to-cell differences create unequal degradation. Average temperature alone is insufficient because a cooler cell can coexist with a persistent hotspot. Temperature uniformity therefore becomes a primary design variable rather than merely a reporting metric. Heat pipes transport heat to a remote condenser ^[3-5]. Copper spreads heat rapidly but adds mass; nano-carbon can improve in-plane transport only when its interfaces are controlled ^[6]. Such laminates are anisotropic and interface-sensitive, so they should not be assigned idealized graphene conductivity. The heat pipe must likewise include condenser resistance rather than infinite conductance. Thermal-management studies usually emphasize temperature, whereas aging studies often prescribe the thermal boundary ^[7-8]. This work combines a conservative coupled architecture, an electro-thermal-aging model with contact resistance, and a multi-objective search ^[9]. All results are numerical predictions.

2. Coupled cooling configuration and modeling

The module contains twelve 4.0 Ah 21700 NMC/graphite cells in a 3×4 array. Each 21 mm $\times$ 70 mm, 68 g cell uses $c_p = 920 \text{ J kg}^{-1} \text{ K}^{-1}$ and homogenized radial and axial conductivities of 1.1 and 24 W m⁻¹ K⁻¹ ^[10]. In **Figure 1**, a 0.10 mm nano-carbon layer on 0.90 mm copper spreads heat to two flattened evaporators, whose condenser rejects heat to air. Case A is the reference enclosure; Cases B and C add the spreader and heat pipes separately; Case D couples them.

The governing cell balance is

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + q_{\text{gen}} \quad (1)$$

Heat generation follows the Bernardi form ^[2],

$$q_{\text{gen}} = I(V_{\text{oc}} - V) - IT \frac{dV_{\text{oc}}}{dT} \quad (2)$$

where I is current, $V_{\text{oc}} - V$ is polarization loss, and dV_{oc}/dT is the entropic coefficient. Finite volumes reduce Eq. (1) to cell core and shell nodes. Local spreader nodes retain in-plane conduction; the heat pipe becomes a high-conductance path to one condenser node, valid below its capillary and boiling limits ^[3]. Contact resistances are discrete thermal resistors.

Coupled nano-carbon/copper-heat-pipe cooling concept

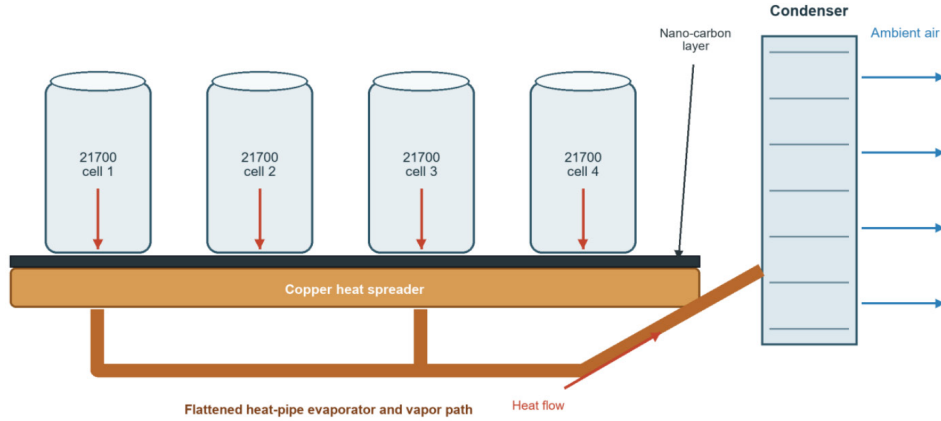


Figure 1. Nano-carbon/copper spreader and flattened heat-pipe cooling path.

Temperature-dependent degradation is represented by

$$k_{\text{age}} = A \exp\left(-\frac{E_a}{RT}\right) f(\text{SOC}, C - \text{rate}) \quad (3)$$

with $E_a = 32 \text{ kJ mol}^{-1}$. The time-integrated module-average rate is normalized by Case A, so the index expresses relative duty damage, not calendar life or cycle count ^[7-8].

3. Numerical method and co-optimization strategy

The cells discharge at 3 C from 90% to 15% SOC for 900 s at 25 °C. Resistance varies from 0.019 to 0.024 Ω and dV_{oc}/dT is about $-8 \times 10^{-5} \text{ V K}^{-1}$; mean heat rises from 3.10 to 3.83 W. The enclosure corresponds to $h \approx 8 \text{ W m}^{-2} \text{ K}^{-1}$. Baseline contact resistance is 0.30 K W^{-1} per cell and condenser h is 45 $\text{W m}^{-2} \text{ K}^{-1}$. Implicit integration conserves heat within 0.05%; halving the 1.0 s step changes T_{max} by 0.003 K.

The search samples 420 designs over nano-carbon thickness 0.04–0.24 mm, copper 0.45–1.45 mm, one to four heat pipes, contact resistance 0.16–0.85 K W^{-1} , and condenser $h = 25\text{--}75 \text{ W m}^{-2} \text{ K}^{-1}$. Non-dominated designs minimize T_{max} , ΔT , aging, and mass. A weighted score selects a compromise.

4. Thermal performance of the coupled system

Case A reaches 65.9 °C with $\Delta T = 3.28 \text{ K}$. The spreader in Case B lowers T_{max} to 57.8 °C and ΔT to 0.41 K because lateral conduction redistributes unequal cell heat. Case C reaches 48.8 °C and $\Delta T = 1.39 \text{ K}$; remote rejection is strong, but direct evaporator proximity creates a larger spatial difference than the spreader. Coupling both functions in Case D gives 46.2 °C and 1.09 K. Relative to Case A, these changes are 19.7 °C and 67%, respectively. **Figure 2** summarizes the four cases and the non-dominated coupled designs.

5. Lifetime-oriented optimization results

The normalized aging indices for Cases A–D are 1.000, 0.906, 0.783, and 0.750. Thus, the lower and more uniform field in Case D reduces the modeled duty damage by 25.0% without converting this short

simulation into an unsupported lifetime claim. The selected design uses a 0.183 mm nano-carbon layer, 0.480 mm copper, three heat pipes, 0.222 K W⁻¹ contact resistance, and $h_{\text{cond}} = 72.1 \text{ W m}^{-2} \text{ K}^{-1}$. It adds 103.5 g and predicts $T_{\text{max}} = 42.5 \text{ }^{\circ}\text{C}$, $\Delta T = 0.78 \text{ K}$, and an aging index of 0.706. Increasing contact resistance from 0.15 to 1.00 K W⁻¹ raises T_{max} from 46.0 to 47.2 $^{\circ}\text{C}$ and the index from 0.748 to 0.763. The selected thin copper layer also shows the diminishing benefit of mass once condenser-side rejection dominates.

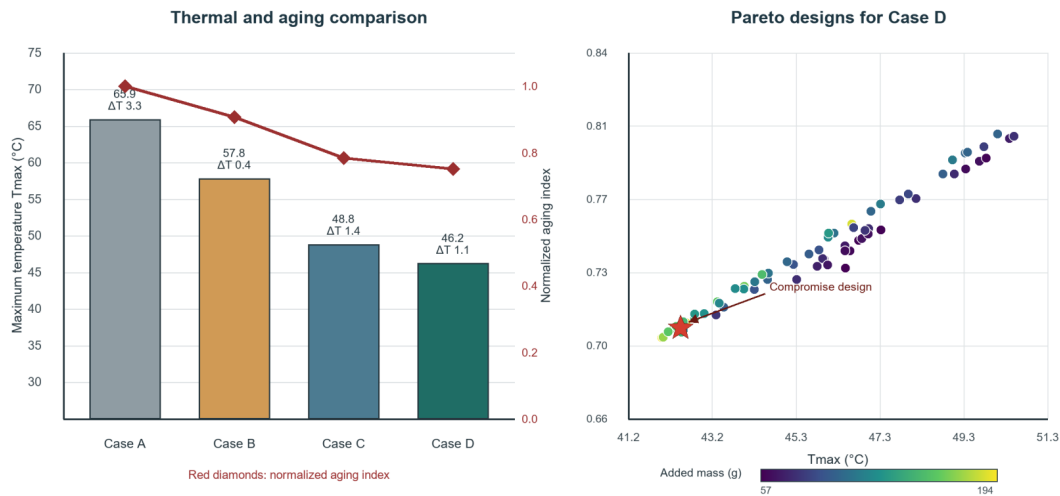


Figure 2. Simulated case comparison and Pareto trade-off for coupled designs.

6. Discussion

The spreader and heat pipe address different bottlenecks. The sheet equalizes local heat flux before discrete evaporators, while the heat pipe moves the load to a larger condenser. Case B therefore gives the smallest baseline ΔT but not the peak-temperature reduction of Cases C and D. Poor contact or weak condenser convection erodes the coupled advantage; added sheet thickness cannot remove that external resistance. Within the sampled range, the selected design favors higher condenser h and three pipes over maximum copper thickness, indicating diminishing returns after lateral conduction becomes adequate. The model uses literature-scale properties and assumptions, not module measurements. It simplifies heat-pipe limits, electrochemical gradients, aging chemistry, stress, and manufacturing variation. Calorimetry, contact-resistance tests, thermal imaging, and controlled cycling are required before qualification.

7. Conclusion

The finite-volume model compares reference, spreader-only, heat-pipe-only, and coupled cooling. Baseline Case D reduced predicted T_{max} from 65.9 to 46.2 $^{\circ}\text{C}$, ΔT from 3.28 to 1.09 K, and aging from 1.000 to 0.750. A mass-penalized design with three heat pipes reached 42.5 $^{\circ}\text{C}$ and 0.706 while adding 103.5 g. Lateral heat equalization before remote rejection explains the gain; contact and condenser resistances set its limits. The framework ranks choices under one duty cycle; it does not predict service years or certification performance. Experiments are needed to identify those resistances and recalibrate aging.

Fundings

This work was supported by the Science and Technology Project of the Jiangxi Provincial Department of Education: "Research on the Synergistic Optimization of Battery Life and Thermal Safety Based on Nano-Carbon Copper–Heat Pipe Coupling" (No. GJJ2502810).

About the author

*Corresponding author: MOHD KHAIR HASSAN.

References

- [1] T. M. Bandhauer et al., "A Critical Review of Thermal Issues in Lithium-Ion Batteries," *J. Electrochem. Soc.* 158(3) (2011) R1. doi: 10.1149/1.3515880.
- [2] D. Bernardi et al., "A General Energy Balance for Battery Systems," *J. Electrochem. Soc.* 132(1) (1985) 5–12. doi: 10.1149/1.2113792.
- [3] A. Greco et al., "A Theoretical and Computational Study of Lithium-Ion Battery Thermal Management for Electric Vehicles Using Heat Pipes," *J. Power Sources* 257 (2014) 344–355. doi: 10.1016/j.jpowsour.2014.02.004.
- [4] Z. Zhang and K. Wei, "Experimental and Numerical Study of a Passive Thermal Management System Using Flat Heat Pipes for Lithium-Ion Batteries," *Appl. Therm. Eng.* 166 (2020) 114660. doi: 10.1016/j.applthermaleng.2019.114660.
- [5] Z. Y. Jiang and Z. G. Qu, "Lithium-Ion Battery Thermal Management Using Heat Pipe and Phase Change Material during Discharge–Charge Cycle," *Appl. Energy* 242 (2019) 378–392. doi: 10.1016/j.apenergy.2019.03.043.
- [6] K. M. Yang et al., "Anisotropic Thermal Conductivity and Associated Heat Transport Mechanism in Roll-to-Roll Graphene Reinforced Copper Matrix Composites," *Acta Mater.* 197 (2020) 342–354. doi: 10.1016/j.actamat.2020.07.021.
- [7] J. Schmalstieg et al., "A Holistic Aging Model for Li(NiMnCo)O₂ Based 18650 Lithium-Ion Batteries," *J. Power Sources* 257 (2014) 325–334. doi: 10.1016/j.jpowsour.2014.02.012.
- [8] B. Rumberg et al., "Holistic Calendar Aging Model Parametrization Concept for Lifetime Prediction of Graphite/NMC Lithium-Ion Cells," *J. Energy Storage* 30 (2020) 101510. doi: 10.1016/j.est.2020.101510.
- [9] U. Han et al., "Thermal Performance Analysis and Optimization of Heat Pipe-Assisted Hybrid Fin Structure for Lithium Battery Thermal Management," *Int. Commun. Heat Mass Transf.* 149 (2023) 107128. doi: 10.1016/j.ichea.2023.107128.
- [10] T.-F. Yang et al., "Numerical and Experimental Study on Thermal Management of NCM-21700 Li-Ion Battery," *J. Power Sources* 548 (2022) 232068. doi: 10.1016/j.jpowsour.2022.232068.