International Journal on Science and Technology (IJSAT)

E-ISSN: 2229-7677 ● Website: www.ijsat.org ● Email: editor@ijsat.org

Comparative CFD-Based Conjugate Heat Transfer Analysis of Air, Liquid, PCM, and Hybrid Cooling Strategies for a Compact 3×4 Lithium-Ion Battery Module

Shubham Kumar[1], Dr. Surjeet Singh Rajput[2]

[1]M-tech, Scope Global Skills University, Bhopal
[2]Associate Professor, Scope Global Skills University, Bhopal

Abstract

The speedy expansion of electric vehicles (EVs) has created the need for dependable lithium-ion battery thermal management systems (BTMS), as uneven temperature distribution speeds up capacity fading and increases the chances of thermal runaway. This paper provides results from a three-dimensional conjugate heat transfer (CHT) analysis using pressure-based computational fluid dynamics (CFD) that compares thermal behaviors of 4 cooling processes, including air cooling, indirect liquid cooling (cold plates), phase change material (PCM) cooling and a hybrid liquid–PCM cooling process. All cases were done under the same geometry, mesh details and boundary conditions. From the results generated in the exercise, it's revealed that the air-cooling process is not sufficient and reaches a maximum temperature of about 48.5 °C with temperature difference of about 8.2 °C. The liquid cooling system minimizes the maximum temperature to approximately 32.1 °C with a temperature spread of about 2.4 °C._PCM cooling is beneficial in that it suppresses warming up to eventually enables the temperature rise up to phase change material's saturation.. Based on the trade-off between thermal performance and practical feasibility, indirect liquid cooling is identified as the most viable solution for compact, high-density EV battery modules.

Keywords— lithium-ion battery; battery thermal management system (BTMS); conjugate heat transfer; computational fluid dynamics; phase chan ge material; hybrid cooling; electric vehicle

1. Introduction

Lithium-Ion battery pack is considered as one of the most important parts of the Electric Vehicle (EV) because it has a direct impact on driving distance, speed of charging, and even reliability of the vehicle. Nevertheless, during both charging and discharging processes, the battery generates a significant amount of heat that might lead to overheating in case it exceeds some levels. Keeping the temperature of each cell between certain safe limits (below 35-40° C) and temperature distribution inside a module within 5°C is vital for safe operation of EVs.

Conjugate heat transfer (CHT) simulation, where the conduction process in the solid battery cells along with the convection process in the adjacent cooling medium is simultaneously solved numerically, is an efficient approach to assessing and comparing different BTMS designs at a minimal cost of physical experiments. In this research, the proposed three-dimensional CFD-based CHT model is used to analyze a 3×4 cell array comprising of 12 prismatic lithium-ion battery cells, and the performance of four different cooling schemes, including air cooling, indirect liquid cooling, PCM cooling, and hybrid liquid/PCM cooling, is compared using a consistent 3C discharge rate. Contrary to studies where a single cooling method is analyzed separately, the present work is unique in terms of analyzing all the cooling methods within a single modeling environment.

2. Literature Review

There is a vast literature on the battery thermal management system (BTMS), which has been researched extensively as a conjugate heat transfer problem, where heat transfer occurs by conduction within the cells and by convection in the cooling fluid [1], [2]. Air cooling has the advantage of simple and cheap system, but low heat capacity and low thermal conductivity cause high temperature gradients along the flow direction [4]. Liquid cooling using cold plates or embedded channels has high heat transfer coefficient, and is generally accepted as the best solution due to the high power requirement, even though it has difficulty in obtaining uniform flow

PCMs, primarily made of paraffin, use latent heat in the phase transition process and are good at leveling out short spikes in temperatures; nevertheless, the low thermal conductivity of PCMs (≈ 0.2 W/m·K) renders them ineffective as a coolant after full melting due to their behavior similar to insulators [5], [6]. The idea of hybrid liquid-PCM cooling has been considered in order to take advantage of the ability of PCMs to level out temperature spikes along with continuous cooling provided by the liquid; however, such an approach would increase the weight of the battery as well as the complexity of the manufacturing process. Battery thermal problems and comparisons of various types of cooling methods [8]–[10] show that although there is sufficient information on each technique separately, there is no comparative analysis of all the major cooling methods in a unified, compact module under high (3C) discharging rates.

3. Problem Statement And Objectives

However, in the case of a 3×4 pouch cell module, since the central cells are bounded from multiple sides by the adjoining cells and the casing of the module, there will be fewer ways for the central cells to dissipate heat compared to the edge cells. Due to high current discharge, the geometry of the cells causes temperature variations of 8-10 °C between the central cells and edge cells.

The goal of this research, accordingly, is to: (i) construct a three-dimensional CHT simulation of the 3×4 module; (ii) perform simulations of air, liquid, PCM, and hybrid cooling approaches for 3C discharge with identical boundary conditions; (iii) analyze all cooling techniques in terms of consistent criteria such as cell temperature maxima (Tmax), temperature differences maxima (ΔTmax), pressure drops, and weight/complexity of system; and (iv) recommend the most efficient cooling technique taking into consideration both thermal efficiency and feasibility.

4. Numerical Methodology

A. Geometric Model

The following figure shows the 3D geometry of the battery module where twelve prismatic lithium-ion pouch cells are organized in a 3×4 manner (Fig. 1). The dimensions of each cell are 148 mm × 98 mm × 26 mm and a distance of 3 mm is kept between two adjacent cells to facilitate heat dissipation and cooling interactions. In the present study, four types of cooling geometries were considered: air cooling, liquid cooling using aluminum cold plates, PCM enclosures, and the combination of liquid-PCM cooling.

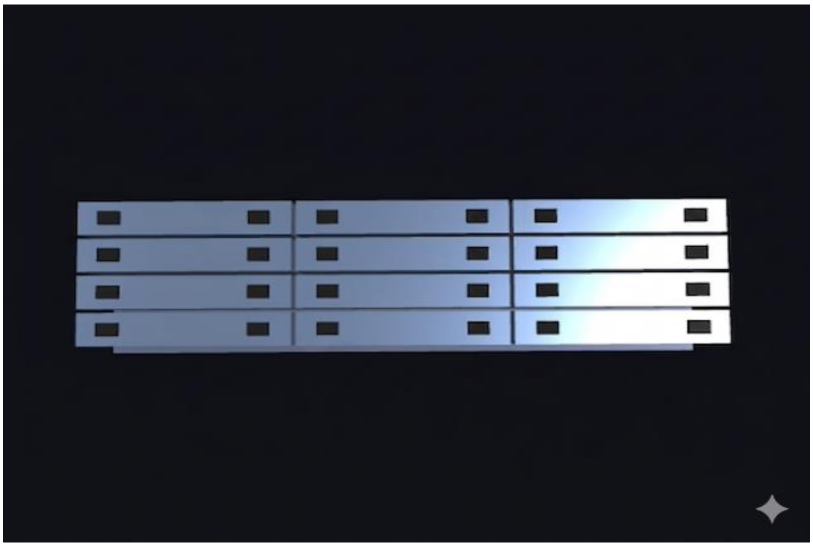

Fig. 1. Three-dimensional CAD model of the 3×4 (twelve-cell) lithium-ion battery module used for all four cooling configurations.

B. Mesh Generation and Independence Study

Mesh discretization in the numerical domain used a hybrid polyhedral mesh, featuring a prism layer around solid-fluid boundaries for capturing the velocity and temperature gradient field (first-layer y+ ~ 1). Mesh independence study was conducted (Table I), in which three different levels of coarse, medium, and fine meshes were considered. As a result of the study, the fine mesh showed less than 1% variation in Tmax from the medium one (3.6 million cells), hence the latter was chosen for all further calculations.

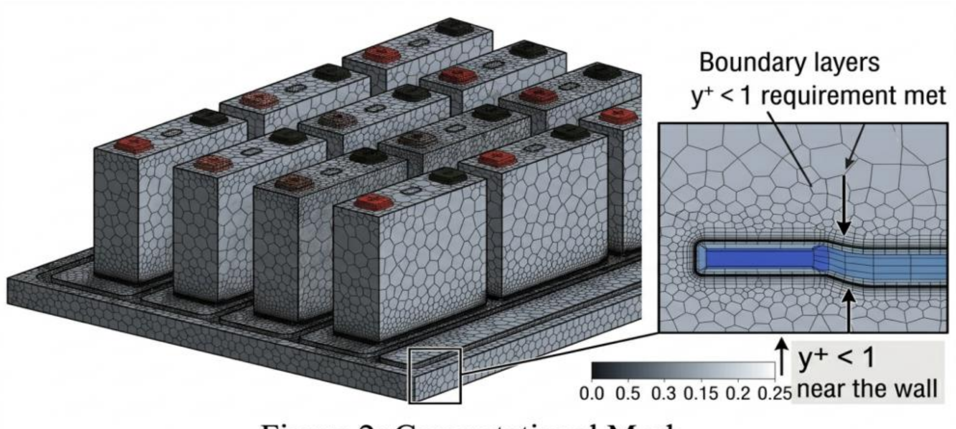

Fig. 2. Cross-sectional view of the polyhedral mesh with near-wall prism-layer refinement (y+ ≈ 1).

Mesh Level	Cell Count	Tmax (°C)	Variation
Coarse	2.8 million	32.4	—
Medium	3.6 million	32.1	0.9%
Fine	4.5 million	32.0	0.3%

Table I. Mesh Independence Study (Liquid-Cooling Case)

C. Governing Equations

The flow field is governed by the continuity and Navier–Stokes equations for an incompressible, Newtonian coolant:

$$\nabla\cdot v = 0$$

$$\partial(\rho v)/\partial t + \nabla\cdot(\rho vv) = -\nabla p + \nabla\cdot[\mu(\nabla v + \nabla v^T)] + \rho g$$

Energy transport is solved separately in the fluid and solid domains and coupled at the interface:

Fluid: $\partial(\rho c_p T)/\partial t + \nabla\cdot(\rho c_p v T) = \nabla\cdot(k_f \nabla T)$

Solid: $\partial(\rho c_p T)/\partial t = \nabla\cdot(k_s \nabla T) + S_h$

with continuity of temperature and heat flux enforced at the solid–fluid boundary, i.e. $T_{solid} = T_{fluid}$ and $k_s(\partial T/\partial n)_{solid} = k_f(\partial T/\partial n)_{fluid}$. The flow regime is characterized by the Reynolds number, $Re = \rho vD/\mu \approx 2500$, placing the coolant flow in the transitional regime and justifying the use of the SST k–ω turbulence model, which was selected for its reliability in near-wall and transitional-flow prediction.

D. Heat Generation and Boundary Conditions

Heat generation within the cells was modeled by the Bernardi heat-source model, $q = I(V - U) - IT(dU/dT)$, with a constant heat generation rate of 18,500 W/m³ for a 3C discharge rate. In the liquid and hybrid models, a 50% water/ethylene glycol mixture was used with an inlet temperature of 25 °C, and the solid boundaries had no-slip boundary conditions while the outlet was a pressure boundary. The simulation parameters are listed in Table II.

Parameter	Value
Cell dimensions (L×W×H)	148 × 98 × 26 mm
Number of cells	12 (3 × 4)
Cell spacing	3 mm
Volumetric heat source (3C)	18,500 W/m³
Coolant	50:50 water–ethylene glycol
Coolant inlet temperature	25 °C
Coolant density / cp / kf	1050 kg/m³ / 3350 J/kg·K / 0.42 W/m·K
Reynolds number	≈ 2500
PCM material	Paraffin RT28HC
PCM melting range / latent heat	27–29 °C / 245 kJ/kg
Cold plate material	Aluminium 6061 (k = 202 W/m·K)
Turbulence model	SST k–ω

Parameter	Value
Pressure–velocity coupling	SIMPLEC
Spatial discretization	2nd-order upwind
Convergence criteria	10^{-6} (energy), 10^{-3} (others)

Table Ii. Simulation Setup Parameters

E. PCM Modelling

RT28HC paraffin was described by phase change properties through the enthalpy-porosity approach in which the total enthalpy H was formulated as $H = h + \beta L$ with the liquid fraction β being zero for $T \leq 27$ °C, $\beta = (T - 27)/(29 - 27)$ for the melting temperature of 27–29 °C, and one for $T \geq 29$ °C. Due to the low thermal conductivity of the PCM (= 0.2 W/m·K), the heat conduction would be limited when the PCM completely melts.

F. Simulation Matrix

Cases employing air and fluid cooling systems were simulated in steady state conditions, but cases involving only PCM cooling and hybrid systems were simulated transiently over 1800 seconds (30 minutes), which is equivalent to 3C discharging cycles.

5. Results and Discussion

A. Air Cooling Performance

In the air-cooled case considered here as the baseline system, a strong non-uniformity of the temperature distribution can be observed, where the highest temperatures occur in the cells which are most geometrically constrained within the center. The highest temperature is 48.5°C and the temperature span is 8.2°C within the module, which is beyond the safety limits. Such behavior occurs due to the high specific heat capacity and low thermal conductivity of the air, leading to gradual heating of the stream while flowing over the upstream cells, as well as the formation of buoyant recirculation regions.

B. Liquid Cooling Performance

The use of indirect liquid cooling using aluminium cold plates results in effective thermal management, where the highest temperature is lowered to 32.1 °C and temperature range to 2.4 °C. It happens due to the increased thermal capacity of water–ethylene-glycol coolant and effective heat transfer in cold plates, which leads to uniform temperature distribution with no temperature hotspots; the steady state is achieved in approximately 600 seconds after discharge period.

C. PCM and Hybrid Transient Response

Fig. 3 illustrates the time-varying behavior of maximum cell temperature over the entire 30-minute discharging period for all the four approaches. The air cooling method presents nearly linear temperature increase, stabilizing at 48.5°C after about 1500 seconds. For the case of liquid cooling, the system stabilizes quite fast (≈ 600 s) at 32.1°C. PCM cooling approach presents a three-step behavior of cell temperature: sensible heating phase (0–300 s), a nearly constant temperature melting phase (300–600 s) due to the fact that latent heat absorbed in this phase limits temperature increasing, and a rapid temperature increase when the PCM melts out completely (> 600 s). This means that the PCM approach works only for short-term heating peaks but not for long-term high loads.

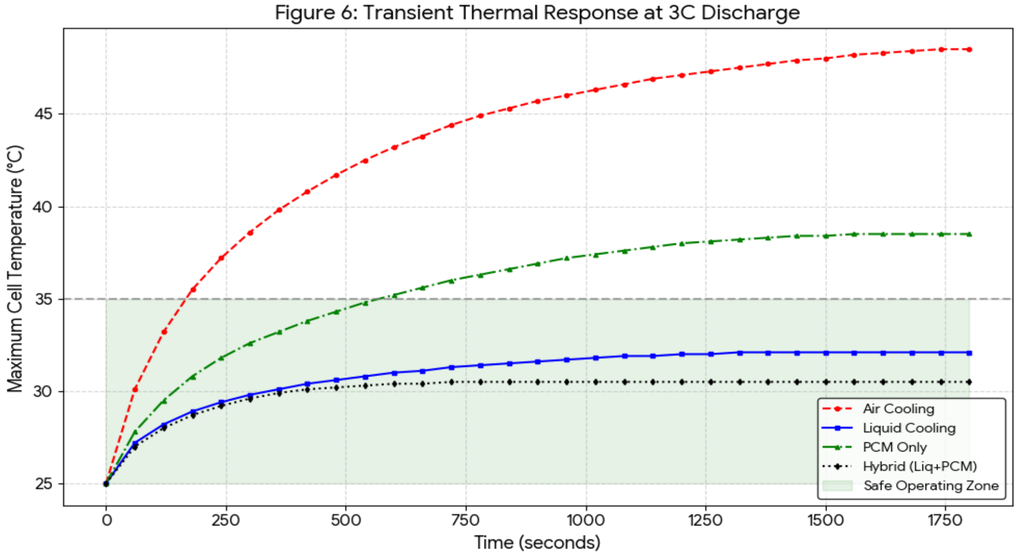

Fig. 3. Transient evolution of maximum cell temperature for all four cooling strategies over a 30-minute 3C discharge cycle.

D. Comparative Performance Metrics

Performance Comparison between the Four Cooling Methods is Presented in Table III and Fig. 4. While both liquid cooling and hybrid approaches meet the 3C thermal criteria, the superiority of the latter approach in terms of thermal performance (1.6 °C reduction in the Tmax and 0.3 °C reduction in the ΔT relative to liquid cooling) is accompanied by much heavier weight (+82%).

Metric	Air Cooling	Liquid Cooling	PCM Only	Hybrid
Tmax (°C)	48.5	32.1	38.5	30.5
ΔTmax (°C)	8.2	2.4	5.5	2.1
Pressure drop (Pa)	5	1200	N/A	1250
Weight (kg)	0.5	2.8	4.2	5.1
Complexity	Low	Medium	Medium	High
Suitable for 3C?	No	Yes	Partial	Yes

Table III. Comparative Performance Metrics for All Four Cooling Strategies

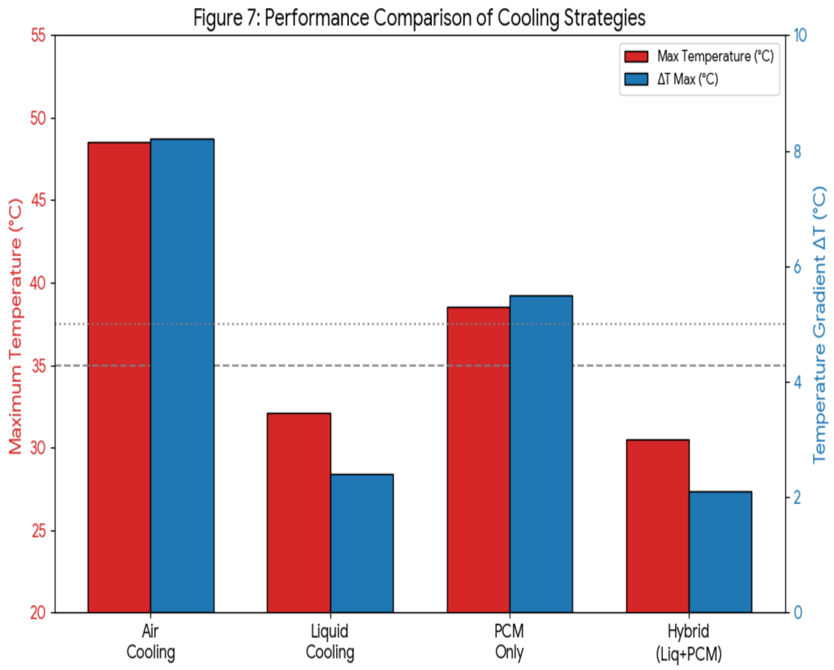

Fig. 4. Comparative bar chart of maximum cell temperature and temperature gradient (ΔT) for the four cooling strategies.

E. Engineering Interpretation

However, air cooling is simply not sufficient for high density modules operating below 3C. Liquid cooling provides the most optimal tradeoff between high performance, reasonable weight, and low complexity, and this technique is chosen by the industry as the best option according to this research. While PCM only offers temporary performance enhancement, the hybrid method offers better performance under constant high loads; however, its higher weight (+82% in comparison with liquid cooling) makes it less attractive, except when the additional performance is necessary (e.g., fast charging).

6. Conclusion

The comparison of air, indirect liquid, PCM, and hybrid liquid-PCM cooling methods using CFD analysis of conjugate heat transfer revealed that air cooling was not enough to maintain safe temperature levels, showing too high temperature peak and thermal inhomogeneity. Liquid cooling guaranteed consistent and homogeneous thermal behavior below the safety threshold values. PCM cooling postponed temperature increase but became ineffective during the phase-change process. The hybrid method allowed obtaining the minimum peak temperature and maximum uniformity; however, the method had some disadvantages in terms of extra weight and complexity. In general, indirect liquid cooling can be recognized as the most feasible cooling method for compact high density EV battery modules.

References

1. A. A. Pesaran, "Battery thermal models for hybrid vehicle simulations," Journal of Power Sources, vol. 110, no. 2, pp. 377–382, 2002.
2. D. Bernardi, E. Pawlikowski, and J. Newman, "A general energy balance for battery systems," Journal of The Electrochemical Society, vol. 132, no. 1, pp. 5–12, 1985.
3. Q. Wang, P. Ping, X. Zhao, G. Chu, J. Sun, and C. Chen, "Thermal runaway caused fire and explosion of lithium-ion battery," Journal of Power Sources, vol. 208, pp. 210–224, 2012.
4. L. H. Saw, Y. Ye, and A. A. O. Tay, "Computational fluid dynamic and thermal analysis of lithium-ion battery pack with air cooling," Applied Energy, vol. 177, pp. 783–792, 2016.
5. Z. Rao and S. Wang, "A review of power battery thermal energy management," Renewable and Sustainable Energy Reviews, vol. 15, no. 9, pp. 4554–4571, 2011.
6. N. Javani, I. Dincer, G. F. Naterer, and B. S. Yilbas, "Heat transfer and thermal management with PCMs in a Li-ion battery," International Journal of Heat and Mass Transfer, vol. 72, pp. 690–703, 2014.
7. D. Chen, J. Jiang, G. H. Kim, C. Yang, and A. Pesaran, "Comparison of different cooling methods for lithium-ion battery cells," Applied Thermal Engineering, vol. 94, pp. 846–854, 2016.
8. S. Panchal, I. Dincer, M. Agelin-Chaab, R. Fraser, and M. Fowler, "Thermal modelling and validation of temperature distributions in a prismatic lithium-ion battery at different discharge rates and varying boundary conditions," Applied Thermal Engineering, vol. 96, pp. 190–199, 2016.
9. K. Smith and C. Y. Wang, "Power and thermal characterization of a lithium-ion battery pack for hybrid-electric vehicles," Journal of Power Sources, vol. 160, no. 1, pp. 662–673, 2006.
10. T. M. Bandhauer, S. Garimella, and T. F. Fuller, "A critical review of thermal issues in lithium-ion batteries," Journal of The Electrochemical Society, vol. 158, no. 3, pp. R1–R25, 2011.