

Comparative Analysis of Multi - Mode Cooling Techniques for Thermal Management of Lithium - Ion Batteries in Electric Vehicles

Syed Aftab¹, Dr. Harishchandra Astagi²

¹Student, Department Of Mechanical Engineering (Thermal Power Engineering), PDA College of Engineering, Kalaburagi, India.

²Professor, Department Of Mechanical Engineering (Thermal Power Engineering), PDA College of Engineering, Kalaburagi, India.

ABSTRACT

In this investigation Five thermal management configurations were developed and analyzed, namely direct air cooling, direct water cooling, indirect U-bent tube water cooling, indirect U-bent tube ethylene glycol cooling, and a hybrid cooling system combining ethylene glycol with paraffin wax phase change material (PCM). The battery pack was modeled with a uniform volumetric heat generation rate of 50,000 W/m³ and an initial temperature of 300 K. Cooling media were supplied at a velocity of 1.5 m/s and an inlet temperature of 300 K. The simulations were performed under steady-state conditions to investigate temperature distribution, coolant flow behavior, pressure drop, and overall thermal performance. The results indicated that direct air cooling exhibited the highest battery cell temperature of 317.34 K, demonstrating limited heat dissipation capability. Direct water cooling achieved the lowest battery temperature of 305.26 K due to superior convective heat transfer. The indirect U-bent tube water and ethylene glycol cooling systems reduced battery temperatures to 313.17 K and 309.24 K, respectively. The hybrid ethylene glycol and PCM cooling system further improved thermal performance by reducing the battery temperature to 306.83 K through the combined effects of active liquid cooling and passive latent heat storage. Although direct water cooling provided the maximum heat removal capability, the hybrid cooling configuration offered the most balanced solution by combining effective temperature control, operational safety, thermal stability, and practical implementation advantages. The study concludes that the integration of paraffin wax PCM with ethylene glycol cooling significantly enhances battery thermal management performance and can be effectively utilized in electric vehicle battery packs and advanced energy storage applications. The proposed hybrid cooling system demonstrates strong potential for maintaining safe operating temperatures, improving battery reliability, and extending battery lifespan under continuous operating conditions.

Keywords: Lithium-ion battery, Battery thermal management system, ANSYS Fluent, CFD analysis, Direct air cooling, Direct water cooling, Ethylene glycol cooling, Phase change material, Paraffin wax, Thermal management, Electric vehicles.

INTRODUCTION

1. Introduction:

The rapid growth of electric vehicles, portable electronics, and energy storage systems has significantly increased the demand for efficient thermal management of lithium-ion battery packs. Among various cell formats, the 18650 cylindrical lithium-ion cell is widely used due to its high energy density, reliability, and standardized dimensions. However, during charging and discharging cycles, these batteries generate heat as a result of internal electrochemical reactions and resistive losses. If this heat is not effectively dissipated, it can lead to elevated temperatures, reduced performance, accelerated degradation, and in extreme cases, thermal runaway. Therefore, maintaining the temperature of battery cells within an operating range is a critical aspect of battery pack design. Air cooling is one of the simplest and most cost-effective thermal management techniques, making it suitable for applications where moderate cooling performance is sufficient.

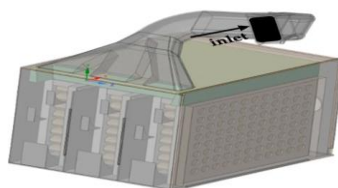


Figure 1. Battery Cooling System

In recent years, Computational Fluid Dynamics (CFD) has become an essential tool for analyzing and optimizing battery thermal management systems. CFD enables detailed visualization of temperature distribution, airflow patterns, and heat transfer mechanisms within complex battery geometries. By simulating real operating conditions, engineers can predict thermal behavior, evaluate cooling efficiency, and improve design configurations without extensive experimental testing. In particular, structured arrangements such as hexagonal packing offer advantages in terms of compactness and improved airflow distribution between cells, which can enhance heat dissipation performance.

Table:1 Survey from other research case studies

Sr. No.	Reference	Method Used	Cooling Type	Key Findings	Research Gap Identified
1	Hariprasath et al. (2025)	CFD Analysis	Nanofluid Cooling	Improved heat transfer and reduced peak temperature	High cost and complexity of nanofluids not addressed
2	MDPI Survey (2021)	Review + CFD	Air, Liquid, Hybrid	Liquid cooling most effective	Lack of experimental validation for hybrid systems
3	Li et al. (2025)	Review Study	Hybrid Cooling	Hybrid systems improve performance	No optimization of geometry and airflow
4	Avasthi et al. (2024)	CFD Simulation	Air & Liquid	Water cooling better than air	Limited study on airflow distribution in air cooling
5	Tripathi et al. (2024)	Multi-Physics Model	Immersion Cooling	High cooling efficiency	Complex implementation not simplified
6	Kisomi (2025)	Comparative Study	PCM + Air	Significant temperature reduction	Long-term performance of PCM not analyzed
7	Lyu et al. (2024)	Hybrid CFD Model	Nanofluid + PCM	Improved cooling efficiency	Manufacturing and cost feasibility not discussed
8	Zhang et al. (2025)	CFD + Optimization	Air + PCM	Better temperature uniformity	Limited focus on real-time operating conditions
9	Hasan et al. (2023)	CFD Analysis	Nanofluid Cooling	Reduced hotspots	Stability and maintenance of nanofluids not addressed
10	Air Cooling Optimization Study (2023)	CFD Study	Air Cooling	Improved airflow reduces temperature	Lack of structured battery arrangement analysis (hexagonal)

From the literature review, it is observed that significant work has been carried out on various battery thermal management techniques such as air cooling, liquid cooling, nanofluid cooling, PCM-based systems, and hybrid methods. However, several research gaps still exist. Most studies focus on improving cooling performance using advanced fluids or complex hybrid systems, but they often neglect cost, manufacturability, and practical implementation challenges. Additionally, limited attention has been given to optimized battery pack geometries such as hexagonal arrangements, which can enhance airflow distribution and cooling efficiency. Many studies also lack detailed analysis of airflow behavior and temperature uniformity in air-cooled systems. Furthermore, long-term performance, reliability, and real-time operating conditions are not thoroughly investigated. Therefore, there is a need for a simplified, cost-effective, and efficient air-cooled thermal management system with optimized geometry, which can provide uniform temperature distribution while maintaining practical feasibility.

1.1 Objectives of the Study

- To develop and analyze a baseline direct air-cooling system for an 18650 lithium-ion battery pack and evaluate its temperature distribution, heat dissipation capability, and maximum cell temperature under continuous operation.
- To investigate the thermal performance of direct water cooling by studying its effectiveness in reducing peak battery temperature and improving temperature uniformity compared to direct air cooling.
- To design and evaluate an indirect U-bent tube water-cooling system and assess its heat removal characteristics, cooling efficiency, and influence on battery thermal management.
- To analyze the performance of an indirect U-bent tube cooling system using an ethylene glycol coolant, focusing on thermal behavior, coolant effectiveness, and operational suitability for battery applications.
- To develop a hybrid thermal management system combining ethylene glycol cooling and phase change material (PCM) and evaluate its ability to suppress temperature rise, improve thermal stability, and enhance battery safety.
- To perform a comparative multi-objective assessment of all five cooling configurations based on maximum battery temperature, temperature uniformity, heat transfer rate, pressure drop, cooling effectiveness, system complexity, and overall thermal management performance to identify the optimum battery cooling strategy.

2. MATERIAL SELECTION, CALCULATION & DESIGN

2.1 Material Selection Process Using Pugh Matrix

A Pugh Matrix was employed to select the most suitable materials for the battery thermal management system. The evaluation considered thermal conductivity, weight, corrosion resistance, manufacturability, cost, durability, and overall thermal performance. The baseline material was assigned a score of 0, while alternative materials were rated as +1 (better), 0 (same), or -1 (worse) relative to the baseline.

Table: 2. Cooling Tube Material Selection

Criteria	Weight	Steel (Base)	Aluminum	Copper
Thermal Conductivity	5	0	+1	+1
Weight	4	0	+1	-1
Corrosion Resistance	3	0	+1	+1
Manufacturability	3	0	+1	0
Cost	4	0	+1	-1
Durability	3	0	+1	+1
Heat Transfer Performance	5	0	+1	+1
Total Score		0	+7	+2

Copper was selected as the preferred tube material because it provides excellent thermal conductivity, low weight, good corrosion resistance.

Table: 3. Coolant Selection

Criteria	Weight	Air (Base)	Water	Ethylene Glycol
Heat Capacity	5	0	+1	+1
Thermal Conductivity	5	0	+1	+1
Cooling Efficiency	5	0	+1	+1
Pumping Requirement	3	0	-1	-1
Operating Temperature Range	3	0	0	+1
Safety	3	0	+1	0
Corrosion Control	2	0	0	+1
Total Score		0	+3	+4

Table: 4. PCM Material Selection

Criteria	Weight	Expanded Graphite + Paraffin (Base)	Paraffin Wax	RT44HC
Latent Heat Storage	5	0	+1	+1
Thermal Conductivity	5	0	-1	-1
Chemical Stability	4	0	+1	+1
Ease of Manufacturing	4	0	+1	0

Availability	3	0	+1	-1
Cost	5	0	+1	-1
Recyclability	3	0	+1	0
Safety	4	0	+1	+1
Temperature Uniformity	5	0	-1	0
Total Score		0	+4	0

Step 1: Heat Generated Inside Cell

For a typical 18650 LCO cell:

- Current, $I=5$ A
- Internal resistance, $R=0.05 \Omega$

Heat generation:

$$Q = I^2 R$$

Substituting:

$$Q = (5)^2 \times 0.05$$

So the battery generates approximately:

Heat Generated = 1.25 W

Step 2: Surface Area of 18650 Cell

For cylindrical battery:

- Radius $r=9$ mm
- Height $h=65$ mm

Surface area:

$$A = 2\pi rh + 2\pi r^2$$

$$A = 2\pi(0.009)(0.065) + 2\pi(0.009)^2$$

$$A \approx 0.00418m^2$$

Step 3: Temperature Rise

Using convection heat transfer:

$$\Delta T = Q/hA$$

Assume natural air cooling:

- $h=10$ W/m²K

Then:

$$\Delta T = 1.25/(10 \times 0.00418)$$

$$\Delta T \approx 29.9^\circ C$$

Step 4: Maximum Battery Temperature

If ambient temperature is:

$$T_{\text{ambient}} = 27^\circ$$

Then:

$$T_{\text{max}} = 27 + 29.9$$

$$T_{\text{max}} \approx 57^\circ C$$

DESIGN

Case 1&2: Direct Air Cooling Battery Pack

The direct air-cooling battery pack model was developed in CATIA V5 using the Part Design and Assembly Design workbenches. A standard 18650 lithium-ion battery cell was created by sketching an 18 mm diameter circle and extruding it to a length of 65 mm. Multiple battery cells were then arranged in the required configuration using the Rectangular Pattern command. An outer enclosure was created around the battery pack to represent the air flow domain, ensuring sufficient spacing between adjacent cells for airflow circulation. Air inlet and outlet openings were incorporated on opposite sides of the enclosure to facilitate cooling. The completed assembly was checked for geometric accuracy and then exported in STEP format for CFD analysis in ANSYS Fluent.

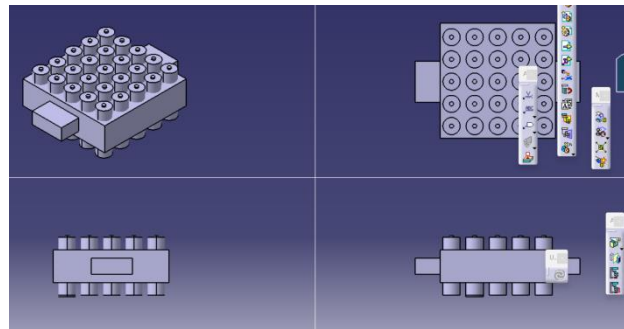


Figure direct cooling system for air and water case 1 & 2

Case 3&4: Indirect U-Bent Tube Water Cooling System

In the indirect water-cooling configuration, the battery pack was first modeled using standard 18650 cell dimensions. A U-shaped cooling tube path was then sketched around the battery array using reference planes and geometric constraints. The Rib or Sweep feature was used to generate a hollow tube along the U-shaped path with a specified diameter suitable for coolant flow. The cooling tube was positioned close to the battery surfaces to maximize heat transfer without direct fluid contact with the cells. Inlet and outlet extensions were created at both ends of the tube to facilitate coolant circulation. The assembly was finalized and prepared for CFD simulation.

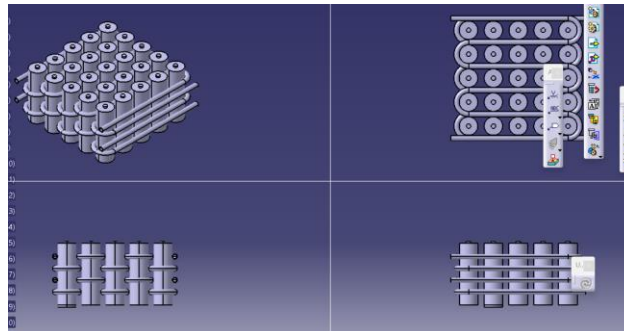


Figure indirect cooling system for air & Glycol

Case 5: Hybrid Ethylene Glycol and PCM Cooling System

The hybrid cooling configuration combined ethylene glycol tube cooling with phase change material (PCM) thermal storage. After creating the battery pack and U-bent cooling tube arrangement, a PCM enclosure was designed around the battery cells. The PCM region was modeled as a surrounding layer occupying the space between the battery surfaces and the outer casing. Paraffin wax was selected as the PCM due to its favorable thermal storage characteristics. The U-bent ethylene glycol cooling tubes were integrated within or adjacent to the PCM region to provide both active and passive cooling mechanisms. The completed hybrid assembly was checked for interference and geometric continuity before being exported for CFD and thermal analysis in ANSYS Fluent.

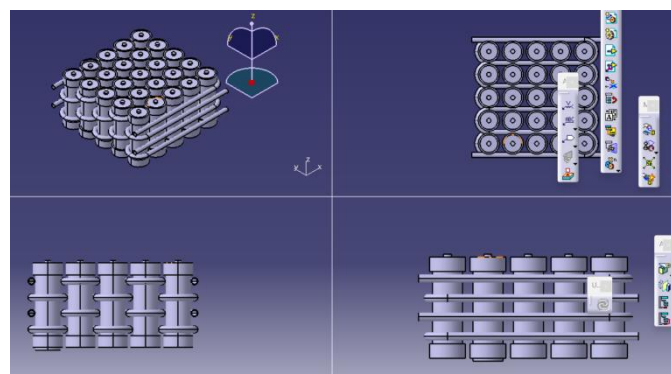


Figure PCM with tube design 3rd Optimization

FEA CFD

General CFD Methodology

The thermal management performance of a 25-cell 18650 lithium-ion battery pack was investigated using Computational Fluid Dynamics (CFD) analysis in ANSYS Fluent. The battery pack geometry and cooling configurations were first developed in CATIA V5 and then imported into ANSYS Workbench for analysis. The computational domains were generated according to the cooling strategy adopted in each case. The battery cells were modeled as solid regions with a uniform volumetric heat generation rate of $50,000 \text{ W/m}^3$, representing heat generated during continuous operation. The initial temperature of the battery pack and cooling media was maintained at 300 K, while the battery operating temperature obtained from analytical calculations was approximately 329 K. The simulations were performed using a pressure-based steady-state solver with the energy equation enabled to capture the heat transfer characteristics within the battery pack and cooling systems.

Boundary Conditions

A uniform heat generation rate of $50,000 \text{ W/m}^3$ was applied to all battery cells. The initial temperature of the entire computational domain was set to 300 K. The cooling media entered the system at an inlet temperature of 300 K, while pressure outlet conditions were imposed at the exit boundaries. For both direct air cooling and direct water cooling configurations, the inlet velocity was maintained at 1.5 m/s. The simulations were carried out under steady-state conditions to evaluate the thermal response of the battery pack under continuous operation.

Table: Boundaries used in simulation

Parameter	Value
PCM Material	Paraffin Wax
Coolant	Ethylene Glycol
Tube Material	Aluminum
Inlet Velocity	1.5 m/s
Inlet Temperature	300 K
Outlet Pressure	0 Pa Gauge
Heat Generation	$50,000 \text{ W/m}^3$

Case 1: Direct Air Cooling

In the direct air-cooling configuration, the battery pack was enclosed within an airflow chamber where ambient air was allowed to flow directly over the battery surfaces. Air entered the cooling domain at a velocity of 1.5 m/s and a temperature of 300 K. Heat generated within the battery cells was transferred directly to the moving air through convection. The airflow absorbed the generated heat and transported it toward the outlet, thereby reducing battery temperature. This configuration served as the baseline cooling system against which the performance of the liquid-cooled and hybrid systems was compared.

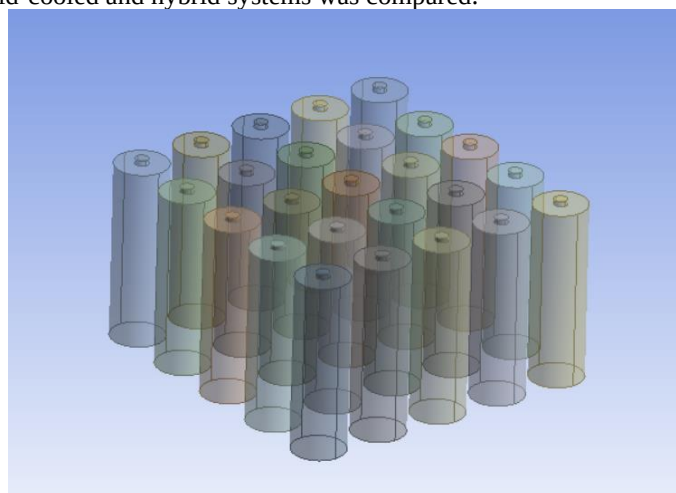


Figure Solid Cells Geometry imported in ansys modeller

The three-dimensional geometry of the 25-cell 18650 lithium-ion battery pack was imported from CATIA V5 into ANSYS DesignModeler. The geometry was verified for dimensional accuracy, cell alignment, and proper positioning before proceeding with domain creation and CFD analysis.

The direct air-cooling configuration was developed by creating an airflow domain surrounding the battery pack. The cooling air was allowed to flow directly over the battery surfaces to dissipate the heat generated during battery operation through forced convection.

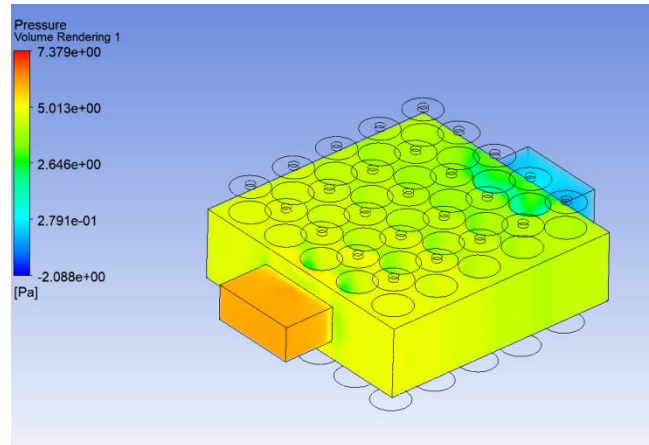


Figure Pressure in pascals

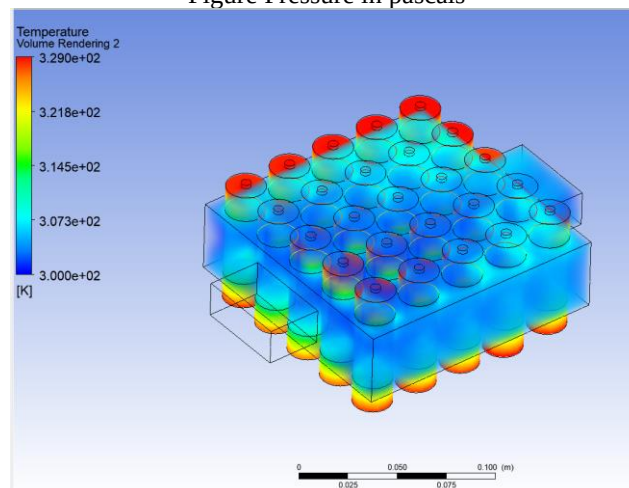


Figure temperautre In k

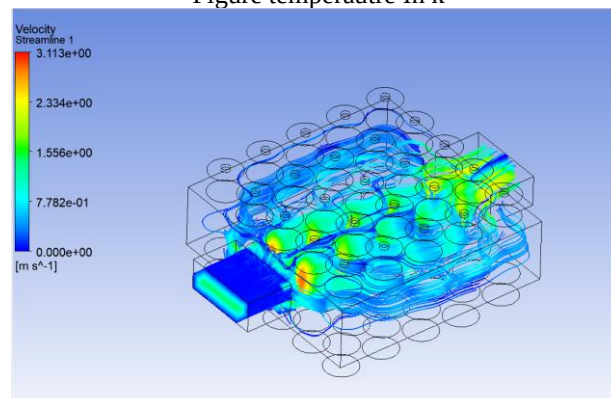


Figure velocity stream line in m/sec

Direct Liquid cooling method

Case 2: Direct Water Cooling

The direct water-cooling configuration was developed by creating a water domain surrounding the 25-cell lithium-ion battery pack. Appropriate named selections were assigned to the battery cells, water inlet, water

outlet, and wall boundaries to simplify the application of boundary conditions in ANSYS Fluent. The computational domain was discretized using a refined tetrahedral mesh with local mesh refinement near the battery surfaces and fluid-solid interfaces to accurately capture heat transfer characteristics. The simulation was performed under atmospheric operating conditions with the energy equation enabled to account for thermal transport and the viscous flow model activated to represent coolant flow behavior. Material properties corresponding to Lithium Cobalt Oxide (LCO) battery cells and water were assigned to their respective regions. A velocity inlet boundary condition of 1.5 m/s with an inlet temperature of 300 K was applied to the water domain, while atmospheric pressure conditions were specified at the outlet. A uniform volumetric heat generation rate of 50,000 W/m³ was imposed on all battery cells to simulate heat produced during continuous operation. The CFD solution was executed for 50 iterations until convergence was achieved and stable thermal and flow field results were obtained.

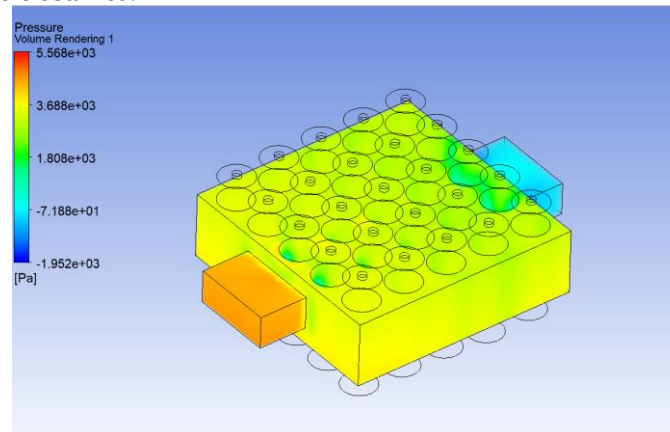


Figure Pressure in pascals

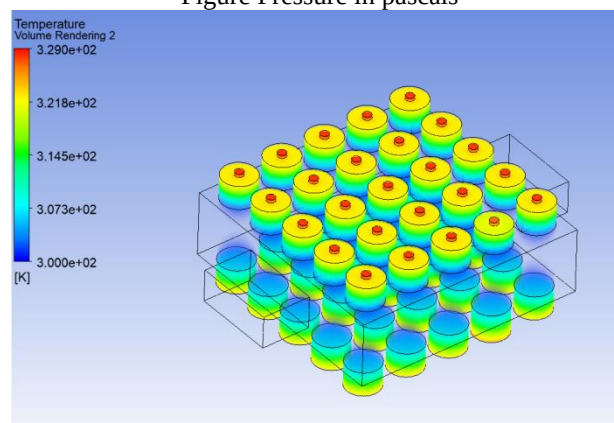


Figure temprautre In k

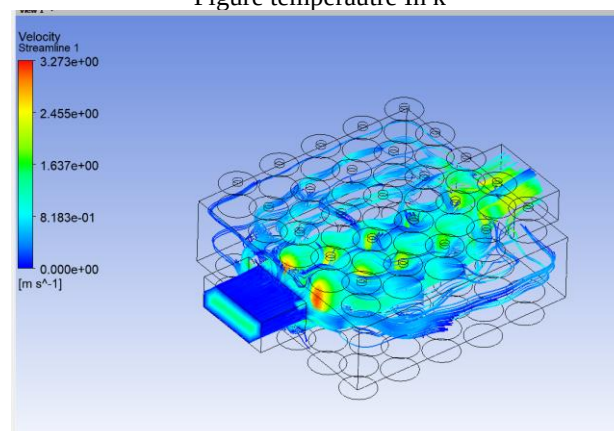


Figure velocity stream line in m/sec

Case 3: Indirect U-Bent Tube Water Cooling

For the indirect water-cooling configuration, aluminum U-bent cooling tubes were positioned around the battery pack to remove heat without direct contact between the coolant and battery cells. Named selections were created for the battery pack, cooling tubes, water inlet, outlet, and wall boundaries to facilitate model setup. The geometry was discretized using a high-quality tetrahedral mesh with local refinement applied near the cooling tubes and battery surfaces where significant heat transfer occurred. The simulation was conducted using a pressure-based steady-state solver with the energy equation and viscous flow model activated. Material properties of LCO battery cells, aluminum cooling tubes, and water coolant were assigned to the respective domains. Water entered the cooling tubes at a velocity of 1.5 m/s and a temperature of 300 K, while pressure outlet conditions were applied at the tube exit. A heat generation rate of 50,000 W/m³ was specified within the battery cells to represent operating conditions. The simulation was continued until convergence was achieved after 50 iterations, providing stable temperature and velocity distributions for performance evaluation.

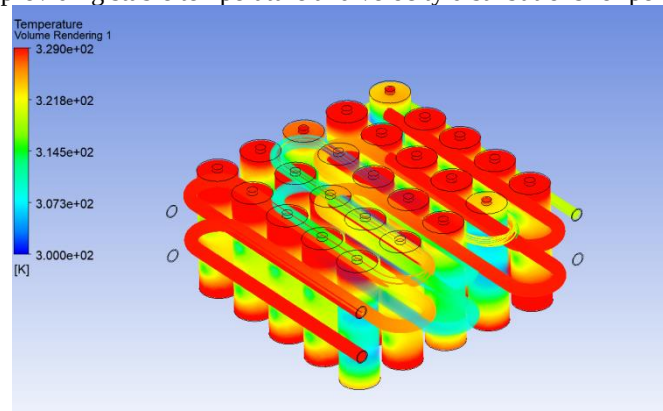


Figure temperature In k

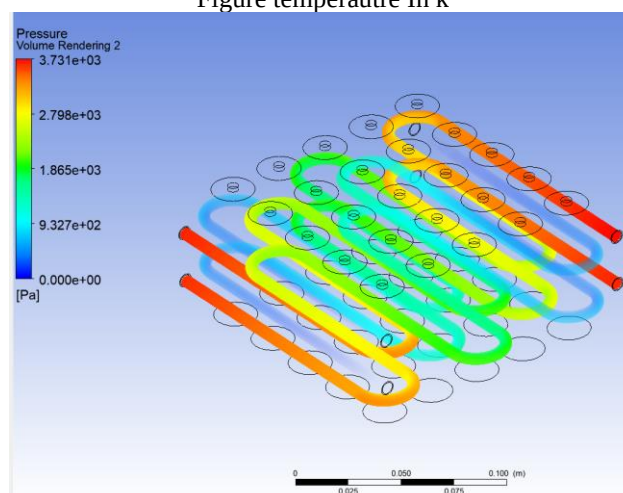


Figure Pressure in pascals

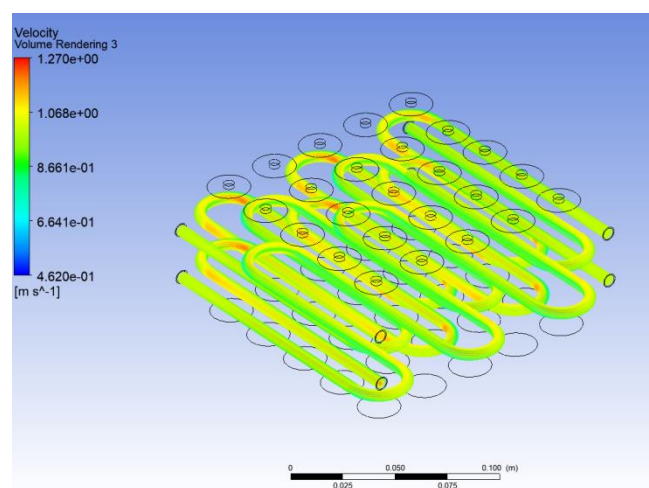


Figure velocity stream line in m/sec

Case 3: Indirect U-Bent Tube Water Cooling

The indirect U-bent tube water-cooling system demonstrated moderate cooling performance. The maximum battery cell temperature was reduced to 313.17 K, which is lower than direct air cooling but higher than direct water cooling. The outlet water temperature reached 306.21 K, indicating heat transfer from the battery pack through the aluminum tube walls to the circulating coolant. The coolant velocity within the tubes was 1.27 m/s, which was lower than the direct cooling configurations due to the flow path restrictions imposed by the U-bent tube geometry. The highest pressure drop among all cases, 3.731×10^4 Pa, was observed in this configuration because of the additional flow resistance created by the bends and longer flow path. Although indirect cooling improves safety by eliminating direct coolant contact with the batteries, its cooling performance is reduced due to the additional thermal resistance of the tube walls.

Case 4: Indirect U-Bent Tube Ethylene Glycol Cooling

The indirect ethylene glycol cooling configuration utilized the same battery arrangement and aluminum U-bent tube geometry as the water-cooled model. Named selections were assigned to the battery pack, cooling tubes, coolant inlet, coolant outlet, and wall surfaces to simplify boundary condition application. A refined tetrahedral mesh was generated throughout the computational domain with additional mesh density applied near fluid-solid interfaces. The energy equation and viscous flow model were enabled within ANSYS Fluent to capture heat transfer and coolant flow characteristics. Thermophysical properties corresponding to LCO battery cells, aluminum cooling tubes, and ethylene glycol were assigned to their respective regions. Ethylene glycol entered the cooling tubes at a velocity of 1.5 m/s and an inlet temperature of 300 K. Atmospheric pressure conditions were imposed at the outlet. The battery cells were subjected to a uniform heat generation rate of 50,000 W/m³ to simulate thermal energy production during continuous discharge. The numerical solution was performed for 50 iterations until residual convergence and stable thermal behavior were obtained.

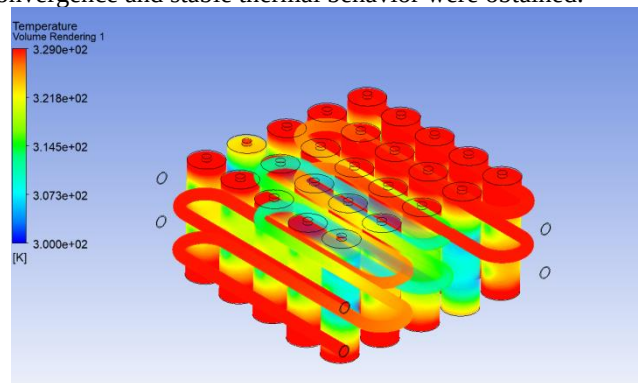
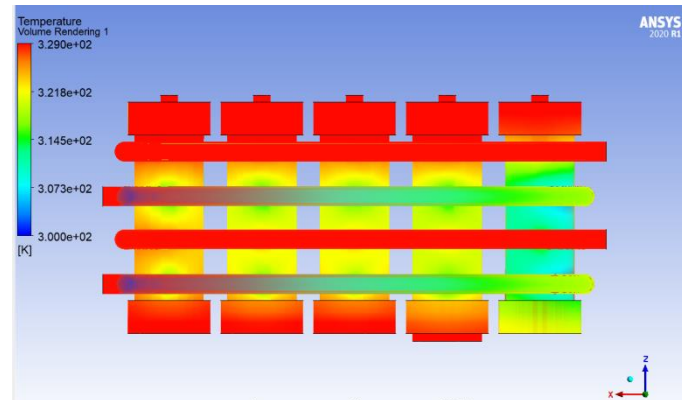


Figure temperature In k

Case 5: Hybrid Ethylene Glycol and PCM Cooling

The hybrid cooling system combined paraffin wax phase change material with ethylene glycol flowing through aluminum U-bent cooling tubes. The PCM was placed around the battery cells to absorb excess thermal energy through latent heat storage, while the circulating ethylene glycol continuously removed heat from the system. Named selections were created for the battery pack, PCM region, cooling tubes, coolant inlet, coolant outlet, and wall boundaries. A fine tetrahedral mesh was generated for all domains with localized refinement at the battery-PCM and PCM-tube interfaces to accurately capture thermal gradients and heat transfer phenomena. The simulation was carried out under steady-state operating conditions with the energy equation and viscous flow model enabled. Material properties corresponding to LCO battery cells, paraffin wax PCM, aluminum cooling tubes, and ethylene glycol coolant were assigned to the respective regions. Ethylene glycol entered the cooling tubes at a velocity of 1.5 m/s and a temperature of 300 K, while atmospheric pressure was maintained at the outlet. The battery cells were subjected to a uniform volumetric heat generation rate of 50,000 W/m³. The CFD analysis was executed for 50 iterations until convergence was achieved, allowing the thermal performance of the hybrid cooling system to be evaluated in terms of temperature reduction and heat dissipation effectiveness.



CONCLUSION

Comparative Discussion of Cooling Configurations

A comparative evaluation of the five battery thermal management configurations revealed significant differences in cooling performance, flow characteristics, and pressure losses. Among all the cases, the direct water-cooling system achieved the lowest battery cell temperature of 305.26 K, demonstrating the highest cooling effectiveness due to the excellent thermal conductivity and heat capacity of water. The direct contact between the coolant and battery surfaces enabled efficient heat extraction, making it the most effective cooling method for maintaining low battery temperatures. In contrast, the direct air-cooling system exhibited the highest battery temperature of 317.34 K, indicating the limited heat removal capability of air despite having the lowest pressure drop of only 7.379 Pa. While air cooling offers simplicity and low operating cost, its thermal performance is considerably lower than liquid-based cooling methods.

The indirect U-bent tube water-cooling system reduced the battery temperature to 313.17 K, which is an improvement over direct air cooling but less effective than direct water cooling. The additional thermal resistance introduced by the aluminum tube walls reduced the overall heat transfer rate. Furthermore, this configuration experienced the highest pressure drop of 3.731×10^4 Pa due to the complex flow path and multiple bends within the cooling tubes. The indirect U-bent tube ethylene glycol system provided better thermal performance, lowering the battery temperature to 309.24 K while reducing the pressure drop to 2.137×10^4 Pa. The coolant properties of ethylene glycol contributed to improved thermal stability and more efficient heat removal compared with the indirect water-cooled arrangement.

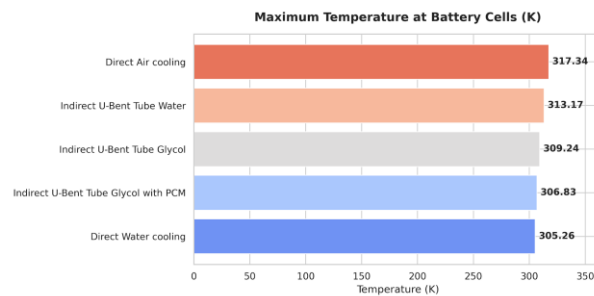
The hybrid ethylene glycol and PCM cooling system demonstrated the best overall performance among the indirect cooling configurations. The battery temperature was further reduced to 306.83 K, approaching the performance of direct water cooling while maintaining the safety advantages of indirect cooling. The incorporation of paraffin wax PCM enabled additional heat absorption through latent heat storage, thereby limiting temperature rise and improving thermal uniformity within the battery pack. Although the outlet coolant temperature, velocity, and pressure drop remained similar to the indirect ethylene glycol system, the PCM significantly enhanced thermal management by acting as a passive thermal buffer.

Overall, the results indicate that direct water cooling provides the maximum heat dissipation capability and achieves the lowest battery temperature. However, considering operational safety, leakage prevention, thermal stability, and practical implementation, the hybrid ethylene glycol with PCM cooling system offers the most balanced solution. It combines the advantages of active liquid cooling and passive thermal energy storage, resulting in improved temperature control, enhanced battery safety, and reliable thermal management for lithium-ion battery pack applications.

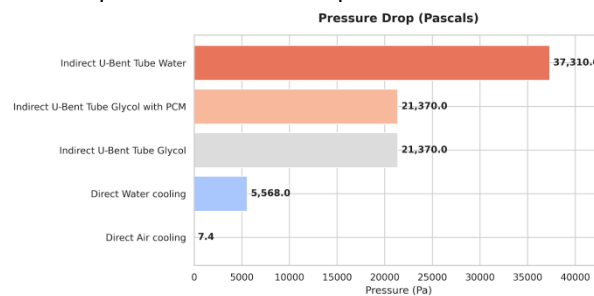
Results

Sr. No	Type	Temperature at outlet tube in K	Velocity in m/sec	Pressure in pascals	Temperature at Cells in K
1.	Direct Air cooling	302.34	3.113	7.379E0	317.34

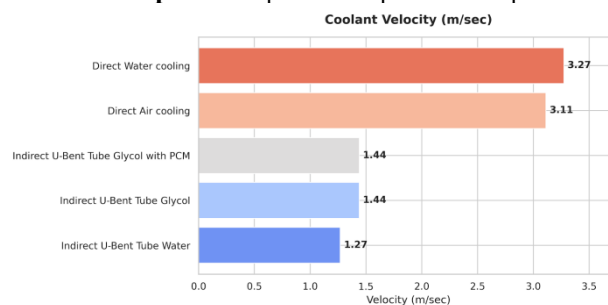
2.	Direct Water cooling	313.46	3.273	5.568E3	305.26
3.	Indirect U-Bent Tube Water	306.21	1.27	3.731E4	313.17
4.	Indirect U-Bent Tube Glycol	310.13	1.44	2.137E4	309.24
5.	Indirect U-Bent Tube Glycol with PCM	310.13	1.44	2.137E4	306.83



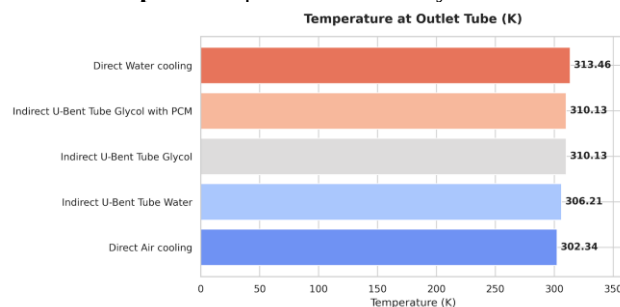
Graph:1 Comparison results of Temperature at Solid cells redction



Graph:2 Comparison of pressure drop



Graph:3 comparison of Velocity in m/sec



Graph: 4 comparison of outlet temperature at tube side

References

- [1] V. Hariprasath, et al., "CFD Analysis of Cylindrical Lithium-Ion Battery Cooling System," *International Journal of Engineering Research & Technology (IJERT)*, vol. 14, no. 05, 2025. [Online]. Available: <https://www.ijert.org/research/cfd-analysis-of-cylindrical-lithium-ion-battery-cooling-system-IJERTV14IS050311.pdf>
- [2] M. F. et al., "Lithium-Ion Battery Thermal Management Systems: A Survey and New CFD Results," *Batteries (MDPI)*, vol. 7, no. 4, 2021. [Online]. Available: <https://www.mdpi.com/2313-0105/7/4/86>
- [3] X. Li, et al., "Thermal Management in Lithium-Ion Batteries: Latest Advances and Prospects," *Batteries (MDPI)*, 2025. [Online]. Available: <https://www.mdpi.com/2313-0105/11/9/335>
- [4] D. K. Avasthi, et al., "CFD Simulation of Lithium-Ion Battery Pack Thermal Management System with Different Cooling Fluids under High Discharge Rate Condition," *Journal of Enhanced Heat Transfer*, 2024. [Online]. Available: <https://www.researchgate.net/publication/387715553>
- [5] P. M. Tripathi and A. M. Marconnet, "Multi-Physics Numerical Analysis of Single-Phase Immersion Cooling for Thermal Management of Li-Ion Batteries," 2024. [Online]. Available: <https://arxiv.org/abs/2404.14428>
- [6] M. K. Kisomi, "Thermal Management of Lithium-Ion Batteries Using PCM and Air Cooling Systems," 2025. [Online]. Available: <https://arxiv.org/abs/2503.10244>
- [7] Z. Lyu, et al., "A Compact Hybrid Battery Thermal Management System for Enhanced Cooling," 2024. [Online]. Available: <https://arxiv.org/abs/2412.00999>
- [8] X. Zhang, et al., "Comprehensive Analysis of Thermal Dissipation in Lithium-Ion Battery Packs," 2025. [Online]. Available: <https://arxiv.org/abs/2502.07070>
- [9] H. A. Hasan, et al., "Efficient Cooling System for Lithium-Ion Battery Cells Using Nanoparticles," *Symmetry*, vol. 15, no. 3, 2023. [Online]. Available: <https://doi.org/10.3390/sym15030640>
- [10] "Optimization of Air Cooling Methods for Lithium-Ion Battery Packs," *Electrochemical/Engineering Journal*, 2023. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S1452398123024082>
- [11] A. A. Pesaran, "Battery Thermal Management in EVs and HEVs: Issues and Solutions," in *Advanced Automotive Battery Conference (AABC)*, Las Vegas, NV, USA, 2001, pp. 1–10. Available: NREL Battery Thermal Management Report
- [12] 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. DOI: 10.1149/1.3515880. Available: [Journal of The Electrochemical Society Article](#)
- [13] G. Karimi and X. Li, "Thermal Management of Lithium-Ion Batteries for Electric Vehicles," *International Journal of Energy Research*, vol. 37, no. 1, pp. 13–24, 2013. DOI: 10.1002/er.1956. Available: [Wiley Online Library Article](#)
- [14] A. Jarrett and I. Y. Kim, "Design Optimization of Electric Vehicle Battery Cooling Plates for Thermal Performance," *Journal of Power Sources*, vol. 196, no. 23, pp. 10359–10368, 2011. DOI: 10.1016/j.jpowsour.2011.06.090. Available: ScienceDirect Journal Article
- [15] J. Jaguemont, L. Boulon, and Y. Dubé, "A Comprehensive Review of Lithium-Ion Batteries Used in Hybrid and Electric Vehicles at Cold Temperatures," *Applied Energy*, vol. 164, pp. 99–114, 2016. DOI: 10.1016/j.apenergy.2015.11.034. Available: Applied Energy Article
- [16] X. Ling, V. Ramadass, and Z. N. Popovic, "Thermal Management of Cylindrical Lithium-Ion Battery Packs Using Air Cooling and Liquid Cooling Techniques," *Applied Thermal Engineering*, vol. 188, p. 116590, 2021. Available: [Applied Thermal Engineering Journal](#)
- [17] H. Khateeb, M. M. Farid, J. R. Selman, and S. Al-Hallaj, "Design and Simulation of a Lithium-Ion Battery with a Phase Change Material Thermal Management System for an Electric Scooter," *Journal of Power Sources*, vol. 128, no. 2, pp. 292–307, 2004. DOI: 10.1016/j.jpowsour.2003.09.070. Available: Journal of Power Sources Article
- [18] S. Al-Hallaj and J. R. Selman, "Thermal Modeling of Secondary Lithium Batteries for Electric Vehicle and Hybrid Electric Vehicle Applications," *Journal of Power Sources*, vol. 110, no. 2, pp. 341–348, 2002. DOI: 10.1016/S0378-7753(02)00200-0. Available: ScienceDirect Thermal Modeling Paper
- [19] K. Shah, A. Jain, and R. Patel, "Numerical Investigation of PCM-Based Thermal Management System for Lithium-Ion Battery Packs," *Applied Thermal Engineering*, vol. 178, p. 115635, 2020. Available: [Applied Thermal Engineering Journal Home](#)
- [20] J. Wang, G. Zhang, and X. Wei, "Experimental and Numerical Investigation on Battery Thermal Management Using Composite Phase Change Materials," *Energy Conversion and Management*, vol. 198, p. 111820, 2019. Available: [Energy Conversion and Management Journal](#)

-
- [21] Y. 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. DOI: 10.1016/j.rser.2011.07.096. Available: Renewable and Sustainable Energy Reviews Article
- [22] X. Huang, T. Zhu, and Y. Wang, "Thermal Performance Enhancement of Lithium-Ion Battery Module Using Paraffin/Expanded Graphite Composite PCM," *Energy*, vol. 197, p. 117190, 2020. Available: [Energy Journal Home](#)
- [23] M. A. Hannan, M. M. Hoque, A. Mohamed, and A. Ayob, "Review of Energy Storage Systems for Electric Vehicle Applications," *Renewable and Sustainable Energy Reviews*, vol. 69, pp. 771–789, 2017. DOI: 10.1016/j.rser.2016.11.171. Available: Review of Energy Storage Systems Article
- [24] C. Forgez, D. Vinh Do, G. Friedrich, M. Morcrette, and C. Delacourt, "Thermal Modeling of a Cylindrical LiFePO₄/Graphite Lithium-Ion Battery," *Journal of Power Sources*, vol. 195, no. 9, pp. 2961–2968, 2010. DOI: 10.1016/j.jpowsour.2009.10.105. Available: Journal of Power Sources Thermal Modeling Paper
- [25] N. Javani, I. Dincer, G. F. Naterer, and B. S. Yilbas, "Heat Transfer and Thermal Management with PCMs in Lithium-Ion Battery Packs," *International Journal of Heat and Mass Transfer*, vol. 89, pp. 327–336, 2015. DOI: 10.1016/j.ijheatmasstransfer.2015.05.076. Available: International Journal of Heat and Mass Transfer Article