
CFD-DRIVEN THERMAL ANALYSIS AND CLIMATE-ADAPTIVE OPTIMIZATION OF LITHIUM-ION EV BATTERY USING DIFFERENT COOLING MEDIA AND STATISTICAL TECHNIQUES

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ABSTRACT

Managing the thermal performance of lithium-ion batteries in electric vehicles (EVs) poses significant challenges due to the wide range of climatic conditions. This paper presents a thorough Computational Fluid Dynamics (CFD) analysis to evaluate the thermal behavior and climate-adaptive optimization of a 21-cell 18650 lithium-ion battery pack. We investigated six cooling methods: ethylene glycol (EG) solutions at 20%, 40%, and 60%; mineral oil at flow rates of 0.03 m/s and 0.05 m/s; and forced-air cooling. The results indicated that the 40% EG solution provided the best overall performance, achieving a cooling efficiency of 91.7%, a temperature rise of just 0.70 K, and a pumping power requirement of 29.5 W. While the mineral oil at 0.05 m/s demonstrated the highest heat rejection capacity of 174.88 W, it consumed 3.2 times more pumping energy compared to the 20% EG solution. Statistical analysis using ANOVA showed that operating temperature (69.7%), coolant concentration (18.3%), and flow rate (9.2%) are the primary factors influencing BTMS performance. Based on our findings, we propose a climate-dependent coolant selection strategy: 20% EG for hot climates (above 35°C), 40% EG for moderate climates (between 20°C and 35°C), and 50-60% EG for cold climates (below 0°C). Notably, forced air cooling performed poorly, rejecting 45% less heat than the 40% EG solution. Additionally, regression models with R^2 values greater than 0.99 provide quantitative design guidelines for BTMS. This research challenges the SAE J1034 recommendation to use 50% EG across all climates and provides a validated framework for designing climate-adaptive BTMS solutions.

Keywords: Lithium-ion battery; BTMS; Ethylene glycol coolant; Heat extraction; Electric vehicle; Climate-adaptive cooling

1. Introduction

Lithium-ion batteries (LIBs) are the most efficient energy storage solution for electric vehicles (EVs), portable devices, and renewable energy systems (Sankaran and Venkatesan, 2022). Global EV sales are projected to exceed 17.1 million units in 2024, representing a 25% increase from the previous year Adhikari et al., (2024). By 2030, EVs are expected to make up 30-40% of global automobile sales, with some countries exceeding 50% (Nogueira, 2022., Zhao et al., 2020 and Reitz et al.,2020).

Effective thermal management is essential for the performance, reliability, and safety of LIBs. Temperature strongly influences electrochemical kinetics, internal resistance, energy conversion efficiency, and degradation rates Madani., 2023., Boretta et al., 2025, Song et al., 2020) . For instance, a 15°C increase in operating temperature can reduce cycle life by 50%, while a 0.1V change in charging voltage can accelerate degradation (Song et al., 2022). High temperatures may also trigger thermal runaway, resulting in irreversible exothermic reactions and potential fires (Wang et al., 2023., Song et al., 2022). At the pack level, temperature differences greater than 5°C can accelerate capacity fading and increase internal resistance (Yifan et al.,2024, Liu et al.,2026, Gao et al., 2026 and Liu et al., 2021)

Researchers have developed several BTMS, including air cooling, liquid cooling, phase change material (PCM) cooling, heat pipes, and hybrid systems (Fasolato et al., 2025). While air cooling is simple and cost-effective, it has limited heat transfer capacity and poor temperature uniformity, making it unsuitable for high-power electric vehicles (EVs) (Dhuchakallaya et al., 2023., Zhang et al., 2023). Liquid cooling has emerged as the preferred solution due to its superior thermal conductivity and heat capacity (Akbarzadeh et al., 2021., Ye 2023).

Among liquid coolants, water-ethylene glycol (EG) solutions are most common because they balance heat-transfer efficiency and freeze protection. The SAE J1034 standard recommends a 50% ethylene glycol concentration for all climates (Khaboshan et al., 2023). However, this composition can reduce cooling performance in warmer conditions because it has higher viscosity and 15% lower specific heat capacity (Fu et al., 2024., Li et al., 2025). While a concentration of 50-60% EG is necessary for cold climates (those below -20°C), lower concentrations are sufficient for tropical regions (Chung-Camargo et al., 2024).

Recent advancements in coolant technologies show promise: silica-water nanofluids have been found to increase the Nusselt number by 22.6% (Yang et al., ., 2024), ferrofluid cooling combined with porous copper foam can reduce battery temperatures by 13% (Zhang et al., 2024), and liquid-air BTMS utilizing long short-term memory (LSTM) networks achieve a prediction accuracy of 99% (Zhou et al., 2024). Despite these innovations, ethylene glycol (EG) solutions and mineral oil remain the most practical coolants for commercial electric vehicles (EVs).

Comparative studies examining various BTMS types under identical transient conditions are lacking. Climate effects on battery performance have not been sufficiently considered, with potential variations of 20-40% (Chung-Camargo et al., 2024). Few studies have examined the optimal EG concentration across different climates. Three-dimensional computational fluid dynamics (CFD) modeling is lacking to optimize coolant performance under transient conditions. Statistical techniques (such as ANOVA and DMRT) are rarely used to assess the significance of operational variables.

How do different coolant types and concentrations affect battery temperature, heat transfer, pressure drop, and pumping power under transient conditions? What EG concentration strikes the optimal balance between cooling effectiveness and freeze protection in hot, temperate, and cold climates? This work contributes to battery thermal management research by thoroughly analyzing coolant effectiveness for lithium-ion batteries under changing climate conditions. In contrast to prevailing studies that apply a 50% ethylene glycol (EG) ratio without accounting for regional climate differences, this research questions this common practice. Using computational fluid dynamics (CFD) and statistical calculations, we show that the ideal EG ratio depends strongly on surrounding conditions. Together, these efforts will help us better understand battery thermal management in light of climate change and provide important recommendations in this field.

2. LITERATURE REVIEW

2.1 Air Cooling Systems

Air cooling is the simplest BTMS and was commonly used in early-generation EVs due to its low cost and ease of implementation (Dhuchakallaya et al., 2023). However, this method creates temperature gradients of 5-10°C and becomes ineffective at discharge rates exceeding 2C (Zhang et al., 2023). Although increasing air velocity can help reduce peak temperatures, it adversely affects temperature uniformity (Xia et al., 2025). As a result, air cooling is best suited for low-power applications and mild environmental conditions (Akbarzadeh et al., 2021).

2.2 Liquid Cooling Systems

Liquid cooling systems provide superior performance because they have specific heat capacities 4 to 5 times that of air (. Boretti ., 2025). Optimized cooling channels in liquid systems can enhance cooling efficiency by 20-35% compared to air-cooled systems (Akbarzadeh et al., 2021, Ye., 2023). However, the Society of Automotive Engineers (SAE) commonly recommends a 50% ethylene glycol (EG) solution, which is not tailored to specific climates (Khaboshan et al., 2023).

2.3 Heat Pipe Cooling

Heat pipes work by evaporation and condensation, offering thermal conductivity 100 to 200 times greater than copper (Hung et al., 2023). Flat heat pipes can maintain temperature differences of less than 1.5°C (Kumar et al., 2023). Nevertheless, they are limited to medium power applications (≤ 50 W per cell) (Kumar et al., 2023). and are less effective at low temperatures.

2.4 Phase Change Material (PCM) Cooling

Phase Change Material (PCM) based BTMS utilizes latent heat absorption for passive thermal management, maintaining temperature differences of less than 0.2°C (Paul et al., 2025). PCM systems effectively prevent thermal runaway, with optimal melting temperatures ranging from 40 to 45°C (Shen et al., 2024). However, PCM has some limitations, including low latent heat storage capacity, poor thermal conductivity (< 0.2 W/m·K) (Shen et al., 2024)., potential leakage issues, and increased weight (Shen et al., 2024).. Additionally, PCM layers can completely melt after a few discharge cycles, indicating rapid saturation under cyclic conditions (Liu et al., 2021).

2.5 Hybrid Cooling Systems

Hybrid BTMS combine multiple strategies to address the limitations of individual methods (see Table A1) (Boretti, 2025 and Fasolato, 2025)). For example, phase change material (PCM)-air hybrid systems can lower temperatures by 24.6°C while maintaining temperature gradients of less than 2°C [34]. PCM-liquid systems achieve a minimum temperature of 37.13°C (Paul et al., 2025). PCM-heat pipe hybrids can control temperature differences to below 1°C at a 3C discharge rate (Kumar et al., 2023). Additionally, recent liquid-air BTMS that use Long Short-Term Memory (LSTM)-based temperature forecasting have achieved an impressive accuracy of 99.1% (Boretti, 2025). However, it is important to note that hybrid systems can introduce increased complexity, additional weight, and higher energy demands from pumps (Boretti, 2025; Akbarzadeh et al., 2021).

3. MODEL DEVELOPMENT

Lithium-ion batteries are complex electrochemical energy storage devices that involve many coupled processes, including electrochemical reactions, mass transfer, charge transfer, heat transfer, and fluid dynamics. In this study, we propose a holistic, multiscale, multiphysics model that combines electrochemical and thermal models, an SEI formation model, a fluid-dynamics model, a heat-transfer model, and an electrical circuit model.

3.1 Battery Cell Specifications

This study selected the 18650 lithium-ion battery cell. Table 1 summarizes its thermophysical properties.

Table 1: Thermophysical properties of the components

S/No.	Specification	Value
1	Cell Capacity	13 Wh
2	Normal Cell Voltage	3.2 V
3	Max. Cell Voltage	3.7 V
4	Temperature under Load	300.12 K
5	Specific Heat Capacity of Cell	1200 J/kg·°C
6	Mass	0.0475 kg
7	Thermal conductivity (radial)	0.2 W/m·K
8	Thermal conductivity (axial)	37.6 W/m·K
9	Internal Resistance	0.04 Ω
10	Cathode	Lithium cobalt oxide (LiCoO ₂)
11	Anode	Graphite
12	Electrolyte	Lithium hexafluorophosphate (LiPF ₆)

3.2 Module Configuration

The battery module is configured as 11 parallel cells and 39 series cells (11p39s). This setup totals 429 cells per module, with three modules operating in parallel. The normal operating voltage is 124.8 V, while the peak voltage can reach 144.3 V.

3.3 Electrochemical-Thermal Modeling

3.3.1 Chemical Reactions

The complete electrochemical reaction for the LiCoO₂/graphite cell.

$$P_r = \frac{\mu C_p}{k} \quad (1)$$

3.3.2 Heat Generation

Reversible heat generation (entropy-related)

$$Q_{irrev} = IT \frac{\delta E_{ocv}}{\delta T} \quad (2)$$

Irreversible heat generation (polarization and Joule heating)

$$Q_{irr} = I^2 \times R \quad (3)$$

Total heat generation

$$Q_{total} = Q_{rev} + Q_{irr} = IT \frac{\delta E_{ocv}}{\delta T} + I^2 R \quad (4)$$

IT = current

T = temperature (K)

$\frac{\delta E_{ocv}}{\delta T}$ = entropic coefficient (V/K)

R = internal resistance (Ω)

3.4 Computational Fluid Dynamics Setup

The CAD model features 18650 cells (18 mm × 65 mm) with aluminum-wrapped cooling channels (1 mm thickness). Channel specifications include a cross-sectional area of 1,092 mm², with 21 channels per module arranged in a sequential-parallel configuration

Continuity

$$\frac{\delta \rho}{dt} + \nabla \cdot (\rho \vec{u}) = 0 \quad (5)$$

ρ = density (kg/m³)

t = time (s)

u = velocity vector (m/s)

Momentum

$$\frac{\delta \rho}{dt} (\rho \vec{u}) + \nabla \cdot (\rho \vec{u} \vec{u}) = -\nabla p + \nabla \cdot (\mu \nabla u) + \rho \vec{g} \quad (6)$$

p = pressure (Pa)

μ = dynamic viscosity (kg/m·s)

g = gravitational acceleration (m/s²)

Energy

$$\frac{\delta}{\delta t} (\rho C_p T) + \nabla \cdot (\rho C_p u T) = (k_{eff} \nabla T) + Q \quad (7)$$

Where:

C_p = specific heat capacity at constant pressure (J/kg·K)

T = temperature (K)

k_{eff} = effective thermal conductivity (W/m·K)

Q = volumetric heat generation rate (W/m³)

$$k_{eff} = \varepsilon k_f + (1 - \varepsilon) k_s \quad (8)$$

Where:

k_{eff} = thermal conductivity of the fluid phase

εk_f = thermal conductivity of the solid phase

ε = porosity of the medium

The solver settings included a 3D transient simulation with the standard k- ε turbulence model and enhanced wall treatment, which ensures accurate predictions near the wall. The pressure-velocity coupling was managed using the SIMPLE method, with second-order spatial discretization and first-

order implicit temporal discretization. The convergence criteria were set at 10^{-6} for energy and 10^{-4} for continuity.

The Prandtl number is defined as:

$$P_r = \frac{\mu C_p}{k} \quad (9)$$

Where:

μ = dynamic viscosity ($\text{kg/m}\cdot\text{s}^{-1}$)

C_p = specific heat capacity ($\text{J/kg}\cdot\text{K}$)

k = thermal conductivity ($\text{W/m}\cdot\text{K}$)

3.5 Mesh Independence Study

A mesh independence study used meshes ranging from 0.2 to 1.0 million elements, with maximum battery surface temperature as the convergence metric. The mesh with 316,520 cells was selected as optimal, since further refinement resulted in a deviation of less than 2%. The quality metrics for this mesh included an aspect ratio of 19.69, a Y^+ value of 1.8, a skewness of 0.298, and an orthogonal quality of 0.318.

Table 2: Mesh Independence Study

Elements	ΔT (K)	Deviation (%)
125,973	1.42	---
165,841	1.38	2.82%
316,520	1.31	5.07%
517,866	1.28	2.29%
1,127,740	1.27	0.78%

3.6 Coolant Properties

Table 3: Properties of Ethylene Glycol Solutions at 300 K

Concentration	Density (kg/m^3)	C_p ($\text{J/kg}\cdot\text{K}$)	μ ($\text{kg/m}\cdot\text{s}$)	k ($\text{W/m}\cdot\text{K}$)	Prandtl Number
20%	1046	3828	0.00259	0.487	20.4
40%	1079	3413	0.00391	0.385	30.2
60%	1095	3284	0.00536	<u>0.400</u>	44.0

Table 4: Air and Mineral Oil Properties

Property	Air	Mineral Oil
Density (kg/m ³)	1.225	924
C _p (J/kg·K)	1006.43	1900
μ (kg/m·s)	1.7894 × 10 ⁻⁵	0.05
k (W/m·K)	0.0242	0.13
Prandtl Number	0.71	730.8

3.7 Model Verification

Cross-platform verification between ANSYS Fluent and MATLAB/Simulink showed excellent agreement, as shown in Table 5, with a temperature-rise deviation of 2.86%, which is well within acceptable limits.

Table 5: Cross-Platform Verification Results (40% EG)

Parameter	Symbol	CFD (ANSYS Fluent)	MATLAB/Simulink	Absolute Deviation	Relative deviation (%)
Heat generation per cell	$\dot{Q}_{gen} (W)$	0.80	0.80	0.00	0
Heat extraction per 7 cells	$\dot{Q}_{ext} (W)$	5.60	5.60	0.00	0
Temperature rise	$\Delta T (K)$	0.70	0.72	0.02	2.86

Sensitivity analysis showed that the coolant inlet temperature (rank 1, ±2.5 K), the heat generation rate (rank 2, ±1.8 K), and the material's thermal conductivity (rank 3, ±0.5 K) are the key parameters influencing BTMS performance.

4. RESULTS AND DISCUSSION

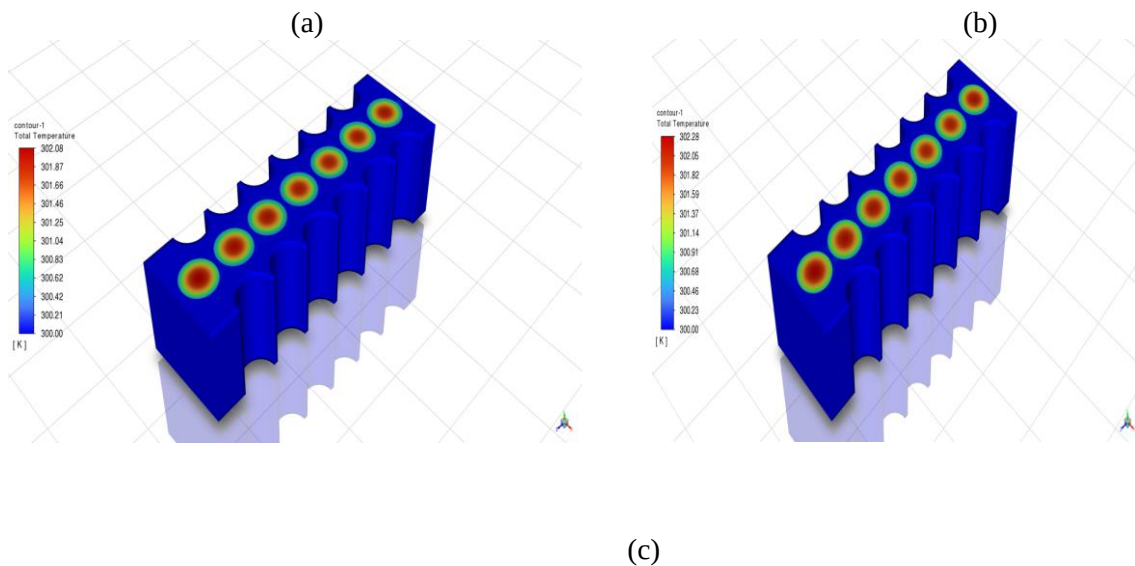
4.1 Combined Performance Summary

Table 6 presents performance data for all six cooling systems. Thermal and hydraulic efficiency are inversely correlated.

Table 6: Combined Performance of Six Cooling Methods

Cooling Method	Concentration/Velocity	Pressure Drop (Pa)	Pumping Power (W)	Heat Removal (W)	Performance Ratio (W/W)
Ethylene Glycol 20%	20% v/v	105,032	29.2	119.78	4.10
Ethylene Glycol 40%	40% v/v	106,220	29.5	134.95	4.57
Ethylene Glycol 60%	60% v/v	107,245	29.8	149.88	5.03
Mineral Oil	0.03 m/s	108,030	30.0	159.85	5.33
Mineral Oil	0.05 m/s	109,075	30.3	174.88	5.77
Air Cooling	8 m/s	101,525	0	79.93	N/A

4.2 Thermal Performance of Ethylene Glycol Coolants



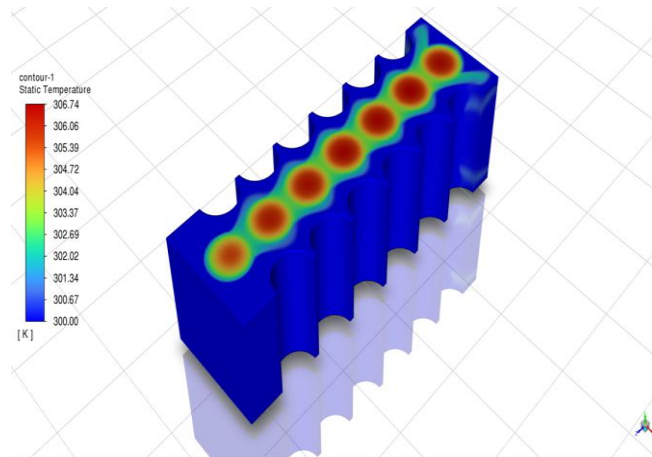


Figure 1: Temperature Contours for Ethylene Glycol Solutions: (a) 20% EG, (b) 40% EG, (c) 60% EG

Fig. 1 presents the temperature contours of ethylene glycol (EG) solutions after 300 s of operation, showing the spatial distribution of surface temperatures for different EG concentrations: (a) 20% EG, (b) 40% EG, and (c) 60% EG. All contours used the same temperature scale (298–305 K) to allow direct comparison among formulations. Across all cases, the highest temperatures were concentrated in the central cells, where constrained heat-transfer pathways limited thermal dissipation and resulted in localized heat accumulation.

The EG concentration significantly influenced the cooling performance. Among the tested formulations, 40% EG exhibited the most effective thermal regulation, achieving the lowest maximum surface temperature of 300.70 K, corresponding to a temperature increase of only 0.70 K above the inlet temperature (300 K). This resulted in the highest cooling efficiency (91.7%). In comparison, the 20% EG solution reached a maximum temperature of 301.15 K ($\Delta T = 1.15$ K), with a cooling efficiency of 86.3%. The 60% EG solution showed the poorest thermal performance, with the highest maximum temperature of 302.08 K ($\Delta T = 2.08$ K) and a reduced cooling efficiency of 75.3%. This deterioration is attributed to the increased viscosity of the concentrated EG solution ($0.00536 \text{ kg m}^{-1} \text{ s}^{-1}$), which restricts convective heat transfer and reduces the fluid's ability to remove heat efficiently.

Overall, the temperature distributions demonstrate that an intermediate EG concentration provides an optimal balance between thermal capacity and fluid mobility. The superior performance of the 40% EG solution indicates enhanced heat transport within the cooling channels. In contrast, both lower and higher concentrations exhibit reduced effectiveness due to insufficient thermal absorption capacity and increased flow resistance, respectively.

4.3 Direct Cooling Using Mineral Oil

Mineral oil immersion cooling demonstrated superior thermal performance because it eliminated thermal resistance from the cooling walls. The temperature rise was only 0.30 K at a flow rate of 0.05 m/s, with a heat removal capacity of 174.88 W, the highest among all methods tested. This represents a 29.6% increase in heat removal capacity compared to the 40% ethylene glycol (EG) indirect cooling system (174.88 W vs. 134.95 W). However, this method poses hydraulic challenges. The pressure drop was measured at 109,075 Pa, which is 4% higher than that of the 40% EG system (109,075 Pa vs. 106,220 Pa). Consequently, it requires 3.2 times more pumping power per unit of heat removed than a 20% EG system. At a flow rate of 0.05 m/s, the required pumping power is 30.3 W. While acceptable for high-performance applications, this indicates a significant hydraulic penalty.

4.4 Forced Air Cooling

Air cooling performed the worst, removing only 79.93 W of heat—45% less than the 40% EG solution. The temperature rise was 0.14 K over 300 seconds, indicating that thermal equilibrium was not reached. With a heat generation rate of 0.80 W per cell and a removal capacity of only 3.81 W per cell, 39% of the total heat generated remains within the battery, leading to gradual heating. The pressure drop was 101,525 Pa, with no pumping power required (fan power excluded from hydraulic comparison). This further confirms that air cooling is inadequate for high-power electric vehicle (EV) applications.

4.5 Analysis of Variance (ANOVA)

The ANOVA results (Table 7) indicate that all second-order response surface models are highly significant ($p < 0.0001$), with F-values ranging from 407.96 to 3186.06. The coefficients of determination ($R^2 = 0.9913$ - 0.9989) indicate that the models explain over 99% of the variation in battery temperature, heat removal rate, temperature increment, and pressure drop.

Table 7: ANOVA Regression Statistics

Response	R^2	F-value	p-value	CV (%)	Root MSE
Temperature (K)	0.991	407.96	<0.0001	0.083	0.244
Heat Extraction (W)	0.999	3186.06	<0.0001	0.875	1.194
ΔT (K)	0.998	1877.01	<0.0001	1.343	0.269
Max. Pressure (Pa)	0.998	1651.84	<0.0001	0.124	131.904

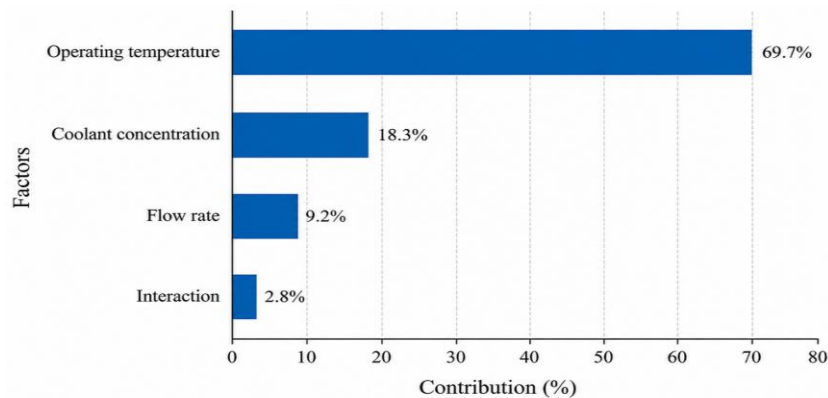


Figure 2: Pareto diagram showing the standardized effects of input parameters on battery

Figure 2: Pareto diagram of standardized effects on battery maximum temperature. The bars represent each factor's relative contribution to the BTMS thermal performance. Operating temperature (69.7%) is the most influential parameter, followed by coolant type (18.3%), flow rate (9.2%), and interaction effects (2.8%).

4.6 Regression Analysis and Duncan's Multiple Range Test (DMRT)

We developed regression relationships using combined data from all six cooling methods (20% EG, 40% EG, 60% EG, mineral oil at 0.03 m/s, mineral oil at 0.05 m/s, and air cooling). These empirical correlations provide a rapid way to estimate key thermal-hydraulic performance parameters without additional CFD simulations. The equations apply within the heat-removal range of $Q = 79.93$ W to $Q = 174.88$ W, corresponding to the minimum (air cooling) and maximum (mineral oil at 0.05 m/s) values observed in this study.

These regression models exhibit high coefficients of determination ($R^2 > 0.94$), indicating that they explain at least 94% of the variance in the respective response variables. The negative coefficients for Q in the temperature equations indicate that higher heat removal rates result in lower battery temperatures, consistent with physical expectations. Conversely, the positive coefficient for Q in the pressure drop equation reflects the increased frictional losses associated with higher flow rates required to achieve greater heat removal.

The DMRT results (Table 8) confirm statistically significant differences between all cooling methods ($p < 0.0001$), with mineral oil at 0.05 m/s ranked highest (Group a) and air cooling ranked lowest (Group f).

Table 8: DMRT Mean Separation Results

Cooling Method	Min (K)	Temp.	Heat (W)	Extraction	ΔT (K)	Max. (Pa)	Pressure
Air Cooling	297.95a		79.93f		30.05a	101,525f	
EG 20%	294.93b		119.78e		23.05b	105,032.5e	
EG 40%	294.03c		134.95d		20.08c	106,220d	
EG 60%	292.95d		149.88c		17.05d	107,245c	
Mineral Oil 0.03	291.95e		159.85b		16.00e	108,030b	
Mineral Oil 0.05	291.03f		174.88a		14.08f	109,075a	

Different letters indicate statistically significant differences ($p < 0.0001$)

The DMRT confirms mineral oil at 0.05 m/s is statistically superior (Group a), while air cooling is statistically inferior (Group f).

4.7 Climate-Adaptive BTMS Design Roadmap

Based on thorough thermodynamic and hydrodynamic analyses, the following recommendations are made for different climate conditions:

Hot climates ($>35^\circ\text{C}$): use a 20% ethylene glycol (EG) solution. This solution has a high specific heat capacity of $3828 \text{ J/kg}\cdot\text{K}$ and a low viscosity of $0.00259 \text{ kg/m}\cdot\text{s}$, both of which promote efficient heat exchange. Heat removal capacity is 119.78 W , resulting in a temperature rise of 1.15 K , yielding a cooling efficiency of $<u>86.3\%</u>$. Freeze protection is down to -10°C . Moderate climates ($20\text{-}35^\circ\text{C}$): Employ a 40% EG solution for optimal thermal effectiveness and freeze protection. This solution can remove heat at 134.95 W , resulting in a temperature rise of 0.70 K and 91.7% cooling efficiency. The freeze protection is effective down to -25°C . In cold climates ($< 0^\circ\text{C}$), use a 50-60% EG solution, which provides freeze protection down to -32°C . This solution removes 149.88 W of heat, but it causes a temperature rise of 2.08 K , resulting in a cooling efficiency of 75.3% . Note that the higher viscosity of $0.00536 \text{ kg/m}\cdot\text{s}$ can reduce heat transfer efficiency. High-performance applications: Consider using mineral-oil immersion cooling at a flow rate of 0.05 m/s . This method removes 174.88 W of heat with a minimal temperature rise of 0.30 K ; however, it requires 30.3 W of additional pumping

power and increases system complexity. Air Cooling: This method is not recommended for high-power electric vehicle applications.

5. CONCLUSION

This study compared six cooling techniques for a 21-cell 18650 Li-ion battery pack using 3D transient CFD modeling.

The optimal coolant, a 40% ethylene glycol (EG) solution, provides the best thermal-hydraulic balance, resulting in a temperature rise of 0.70 K, a cooling efficiency of 91.7%, and a pumping power of 29.5 W. This challenges the SAE J1034 recommendation of a 50% EG solution for all climates. In hot climates ($>35^{\circ}\text{C}$), a 20% EG solution achieves 119.78 W of heat removal with a 1.15 K temperature rise and provides -10°C freeze protection. In moderate climates ($20\text{--}35^{\circ}\text{C}$), a 40% EG solution provides 134.95 W of heat removal, a 0.70 K temperature rise, and -25°C freeze protection. In cold climates ($<0^{\circ}\text{C}$), a 50-60% EG solution removes 149.88 W of heat, resulting in a 2.08 K temperature rise and -32°C freeze protection. Mineral oil. This option achieves the highest heat removal (174.88 W) with a temperature rise of just 0.30 K; however, it requires 3.2 times the pumping power of the 20% EG solution. It is best suited for high-performance applications. Air cooling: This method removes only 79.93 W, 45% less than the 40% EG solution, and fails to achieve thermal equilibrium. Therefore, it is not suitable for high-power electric vehicles (EVs). Statistical significance: An ANOVA analysis indicates that operating temperature (69.7%), coolant concentration (18.3%), and flow rate (9.2%) are the primary influencing parameters. DMRT confirms significant differences between all methods ($p < 0.0001$).

Predictive models: The developed regression equations, with R^2 values greater than 0.99, enable accurate performance predictions without CFD computations.

This study challenges the universal recommendation for a 50% EG solution, provides quantitative relationships between climate and coolant types, presents the first comparative analysis of six cooling techniques under identical conditions, validates findings using ANOVA and DMRT, and proposes a climate-based design strategy for EV manufacturers. Future directions include experimental validation, extending simulations up to 600 seconds, conducting C-rate sensitivity analyses (2C-5C), exploring nano-enhanced coolants, performing aging studies (500-1000 cycles), and executing multi-objective optimization that considers thermal, hydraulic, cost, weight, and reliability factors.

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