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Optimizing Thermal Management of Lithium-Ion Batteries Using Mini-Channel Cold Plates: Analysis of Cooling Fluids and Flow Rate Variations using CFD

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ABSTRACT– Efficient thermal management is critical for improving the safety, performance, and service life of lithium-ion batteries, especially in electric-vehicle applications. This study evaluates a mini-channel cold-plate system by examining the effects of coolant type, mass flow rate, and channel enhancement on heat dissipation using computational fluid dynamics (CFD) supported by experimental validation. Four fluids, namely water, acetone, ethanol, and methane, were examined at mass flow rates of 1×10^{-5}, 1×10^{-4}, and 1×10^{-3} kg/s. Among the tested fluids, acetone produced the lowest maximum battery temperature of 28.0 °C at 1×10^{-3} kg/s, while methane showed the weakest thermal performance. Increasing the mass flow rate consistently reduced battery temperature, but it also increased pressure drop and pumping-power demand. The results indicate that coolant selection should be based not only on thermal performance, but also on pumping-power penalty, safety, and environmental considerations. Although acetone delivered the best cooling performance in this study, its flammability limits its immediate practical adoption. The findings provide design guidance for the development of more effective mini-channel cooling systems for lithium-ion batteries.

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Introduction

Efficient thermal management is crucial for the performance, safety, and longevity of lithium-ion (Li-ion) batteries, particularly in high-demand applications such as electric vehicles (EVs). Li-ion batteries are favored for their high energy density, compact size, and long cycle life, making them the preferred choice for modern EVs and energy storage systems. However, these advantages come with significant challenges in managing the heat generated during charging and discharging cycles. Uncontrolled temperature rises can lead to capacity degradation, reduced performance, and severe safety risks such as thermal runaway, which can result in fires or explosions [1],[2].

The operational temperature range for Li-ion batteries is typically between 25–40 °C, necessitating advanced cooling mechanisms to maintain thermal equilibrium during high-load conditions. Effective thermal management systems are essential to prevent overheating, ensure uniform temperature distribution, and enhance the overall performance and lifespan of the batteries.

Recent advancements in mini-channel cold plate cooling systems offer innovative solutions to these challenges by providing efficient heat dissipation through optimized materials, fluid dynamics, and geometric designs [4],[5]. Mini-channel cold plates utilize compact channels to enhance the surface area for heat exchange, improving convective heat transfer between the cooling fluid and the battery cells. Innovations in these systems focus on improving cooling efficiency through novel materials and optimized geometries. For instance, the development of polymer-based mini-channel cold plates combines lightweight, cost-effective designs with superior safety features, as polymers reduce electrical conductivity risks compared to metals [6].

Optimizing channel geometry and flow configuration is another area of significant research interest. Studies have shown that certain flow configurations outperform traditional straight-channel designs in terms of cooling performance, while the inclusion of features such as fins or turbulators within the channels further enhances heat transfer efficiency [3],[7],[8]. These structural innovations increase the surface area and promote turbulence within the fluid flow, resulting in more efficient heat dissipation. Moreover, optimizing mass flow rates has been identified as a crucial factor influencing thermal performance, with higher flow rates generally correlating with superior cooling capabilities [4],[9].

The choice of cooling fluid is equally important in determining the efficiency of mini-channel cold plate systems. Conventional fluids like water and ethylene glycol

are widely used due to their favorable thermal conductivity and specific heat capacity [5]. Recent advancements in fluid technology, such as the use of nanofluids, have further enhanced cooling performance. Nanofluids, which incorporate nanoparticles like copper oxide (CuO) or aluminum oxide (Al_2O_3) into base fluids, significantly improve thermal conductivity and heat transfer rates, making them promising options for next-generation cooling systems [6],[7]. The performance of these fluids is influenced by their thermal properties, such as viscosity and thermal conductivity, which can be tailored to meet specific application requirements.

Recent studies have further demonstrated the practical potential of mini-channel cooling plates for LiFePO4 battery thermal management in electric vehicle applications [10]. The reported results showed that the use of a mini-channel cooling plate can effectively reduce battery temperature and improve thermal stability, confirming the suitability of this approach for EV battery systems. Nevertheless, further investigation is still required to clarify the combined influence of coolant type, mass flow rate, and geometric enhancement, since many previous studies have addressed these parameters separately rather than within a unified framework.

Despite these advancements, challenges remain in optimizing mini-channel cooling systems for Li-ion batteries. A comprehensive understanding of how different cooling fluids, mass flow rates, and geometric enhancements affect the thermal performance of these systems is needed. Previous studies have often focused on individual aspects such as cooling fluid selection or geometric optimization, but there is limited research examining the combined effects of these factors on the thermal performance of mini-channel cold plates for Li-ion batteries.

This study aims to address these challenges by employing computational fluid dynamics (CFD) to analyze the thermal performance of a mini-channel cold plate system. The research focuses on the effects of cooling fluid type, mass flow rate variations, and geometric design enhancements on cooling efficiency. Four cooling fluids water, acetone, ethanol, and methane were tested at flow rates of 10^{-5}, 10^{-4}, and 10^{-3} kg/s. Geometric enhancements, such as staggered fins and variable cross-sections, were also evaluated for their impact on heat dissipation efficiency.

The primary objectives of this research are to determine the optimal cooling fluid for minimizing battery temperatures in a mini-channel cold plate system, evaluate the effects of varying mass flow rates on cooling system performance, and assess the impact of geometric enhancements on heat dissipation efficiency. By integrating these factors, the study provides novel insights into the design of advanced thermal management systems for lithium-ion (Li-ion) batteries. The findings offer practical guidance for optimizing cooling systems to enhance safety and performance, particularly in applications such as electric vehicles (EVs), where efficient thermal management is critical.

Material and Methods

A. Experimental Design and Simulation Approach

This study employed a combination of computational fluid dynamics (CFD) simulations and experimental validation to evaluate the thermal management performance of mini-channel cold plate systems for lithium-ion (Li-ion) batteries. The research focused on analyzing the effects of different cooling fluids, mass flow rates, and geometric enhancements on heat dissipation efficiency. CFD simulations were conducted using ANSYS Fluent, a widely used CFD software for simulating fluid flow and heat transfer in engineering applications. The simulations aimed to replicate the thermal behavior of the battery system under various operating conditions, providing insights into temperature distributions, fluid flow characteristics, and overall cooling performance.

B. Battery Specifications and Mini-Channel Cold Plate Design

The Li-ion battery modeled in this study was a prismatic cell commonly used in electric vehicle applications. The battery had dimensions of 118 mm × 63 mm × 10 mm, consistent with industry standards for EV battery modules [8]. The thermal properties of the battery materials were defined based on literature values, with a thermal conductivity of 3 W/m·K, a density of 2500 kg/m³, and a specific heat capacity of 1000 J/kg·K.

The heat generation rate of the battery during operation was calculated using the following equation:

$$Q_{gen} = I(E - V) \quad (1)$$

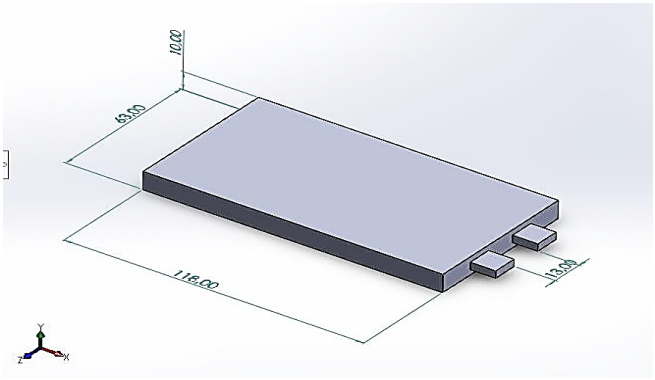
where I is the discharge current (26.5 A), E is the open-circuit voltage (4.2 V). V is the operational voltage (3.7 V). Substituting the values:

$$Q_{gen} = 26.5(4.2 - 3.7) = 13.25W \quad (2)$$

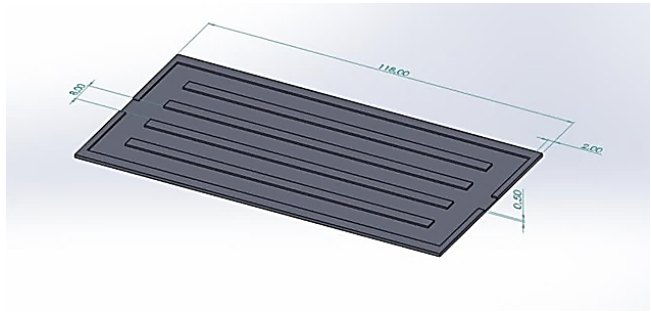
This value represents the total heat generation of a single battery cell under the specified operating condition. For the CFD model, the heat source was applied as a uniform volumetric source term. Using the battery volume of 118 mm × 63 mm × 10 mm (7.434×10^{-5} m^3), the equivalent volumetric heat-generation rate is $13.25 / 7.434 \times 10^{-5} = 1.78 \times 10^5$ W/m^3. This conversion resolves the discrepancy between total heat generation and the source term imposed in the numerical model. The mini-channel cold plate was designed to enhance convective heat transfer from the battery surface. The cold plate was made of aluminum because of its high thermal conductivity (approximately 202.4 W/m.K) and adequate structural strength. The plate thickness was 1 mm, and the channel spacing was 8 mm to promote a uniform flow distribution and good thermal contact with the battery surface.

The battery design is made with dimensions of 118 mm x 63 mm x 10 mm and an aluminum plate with a thickness of 1 mm placed on the side of the lithium-ion battery. The aluminum cooling plate is designed with a distance between

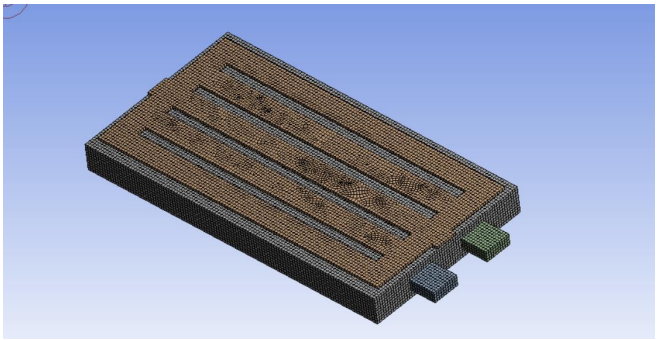
channels of 8 mm. Water will enter through the inlet and exit through the outlet located on the side of the cooling plate. A schematic diagram of the mini-channel cold plate with these geometric enhancements is shown in Figure 1.



(a)



(b)



(c)

Figure 1. Geometry for: (a) Battery cell geometry, (b) Cooling plate with minichannel for working fluid passages, c) Lithium-Ion Battery Cell Meshing Result.

The geometry was meshed using a multizone method to generate hexahedral and prismatic elements. The battery and cooling plate were defined as solid domains, while the coolant channels were set as a fluid domain. All contact regions were assigned a no-slip condition. A global edge sizing of 1 mm was applied to ensure sufficient resolution.

C. Selection and Characterization of Cooling Fluids

Four cooling fluids water, acetone, ethanol, and methane were selected for evaluation based on their thermal properties and suitability for battery cooling applications, representing a range of thermal conductivities, specific heat capacities, viscosities, and densities, all of which are critical factors influencing cooling performance. The thermal properties of these fluids at an operating temperature of approximately 27 °C are summarized in Table 1.

Table 1. Thermal properties of the selected cooling fluids at 27 °C.

Fluid	Thermal Conductivity (W/m·K)	Specific Heat Capacity (J/kg·K)	Density (kg/m³)	Viscosity (Pa·s)
Water	0.6	4182	997	8.9×10^{-4}
Acetone	0.18	2170	784	3.2×10^{-4}
Ethanol	0.17	2440	789	1.2×10^{-3}
Methane	0.034	2220	0.668	1.1×10^{-5}

The selection criteria for cooling fluids included thermal conductivity, as fluids with higher conductivity transfer heat more effectively from the battery surface; specific heat capacity, where a higher capacity enables the fluid to absorb more heat before its temperature rises significantly; and viscosity, with lower viscosity reducing frictional losses and facilitating smoother flow through mini-channels. Safety and environmental impact were also key considerations, addressing factors like flammability, toxicity, and ecological effects.

D. Computational Fluid Dynamics Simulation Setup

CFD simulations were conducted using ANSYS Fluent to model heat transfer and fluid flow within the mini-channel cold plate system. A structured mesh with hexahedral elements ensured numerical accuracy, with refinements near boundaries for detailed thermal characterization. A mesh independence study verified result consistency by ensuring less than 1% variation in maximum battery temperature across finer meshes.

A transient, pressure-based solver with the energy equation enabled was used. The battery was modeled as a solid domain with a uniform volumetric heat source of 1.78×10^5 W/m^3, corresponding to the total heat generation of 13.25 W. The cooling plate was modeled as an aluminum solid, and the external battery and plate walls were subjected to natural-convection boundary conditions with a heat-transfer coefficient of 5 W/m^2.K. For the lower mass flow rates, the expected Reynolds numbers in the mini-channels were within the laminar regime. At the highest mass flow rate, local acceleration and manifold effects can promote transitional behavior; therefore, the standard k-epsilon model was used as a practical turbulence closure for the higher-flow case.

Boundary conditions included constant mass flow rates of 1×10^{-5}, 1×10^{-4}, and 1×10^{-3} kg/s and an inlet temperature of 26.85 °C, the outlet was set to outflow. A uniform heat flux of 13.25 W represented the battery's heat generation, and adiabatic outer walls minimized external heat exchange. Laminar flow assumptions were applied for low Reynolds numbers ($Re < 2300$), while the standard k–ε model addressed turbulence in higher flow rate scenarios. The SIMPLE algorithm handled pressure-velocity coupling, with second-order upwind schemes enhancing accuracy. Convergence was achieved when all residuals were below 1×10^{-6}.

E. Data Analysis and Statistical Methods

The performance of the cooling system was evaluated using three key metrics: maximum battery temperature, representing the highest temperature recorded on the battery surface as an indicator of worst-case thermal conditions; temperature uniformity, reflecting the degree of temperature variation across the battery surface and calculated using the temperature uniformity index; and pressure drop, which denotes the pressure difference between the inlet and outlet of the cooling channels, influencing the pumping power requirements.

Statistical analysis was performed to assess the significance of the differences observed between the various cooling fluids and flow rates. Analysis of variance (ANOVA) tests were conducted, with a significance level set at $p < 0.05$. This statistical approach allowed for the determination of whether the observed differences were statistically significant or could be attributed to random variations.

Results and Discussion

A. Analysis of Lithium-Ion Battery Temperature Without a Cooling System

This section presents a numerical investigation into the thermal behavior of a lithium-ion battery operating under natural convection conditions, without an active cooling system. The analysis was conducted to establish a baseline understanding of the battery's temperature rise and heat dissipation capabilities in the absence of thermal management. A transient simulation was performed using a pressure-based solver with the energy equation enabled. The battery was modeled as an aluminum solid domain with a uniform internal heat generation rate of 7.232 W/m³. The external surfaces were subjected to natural convective cooling with a heat transfer coefficient of 5 W/m²·K, emulating still air conditions. The initial temperature was set to 26.85 °C, consistent with the ambient conditions. Results provide critical insight into the thermal runaway risks and performance limitations of the unmanaged battery system.

The simulation results for the lithium-ion battery without a cooling plate show that the battery temperature increases over time (s), reaching a peak temperature of 322.7 K or approximately 49.55 °C, as shown in Figure 2(b). This temperature exceeds the recommended operational range of 25-40 °C. Consequently, these conditions necessitate the implementation of a thermal management system. To address this issue, the performance of an active cooling system will be analyzed by varying the types of working fluids and their mass flow rates.

The minor differences observed can be attributed to factors such as manufacturing tolerances in the prototype, measurement uncertainties, and assumptions made in the simulations (e.g., perfect thermal contact between the battery and the cold plate). Overall, the validation confirms that the CFD models are suitable for evaluating the thermal performance of the cooling system under various conditions.

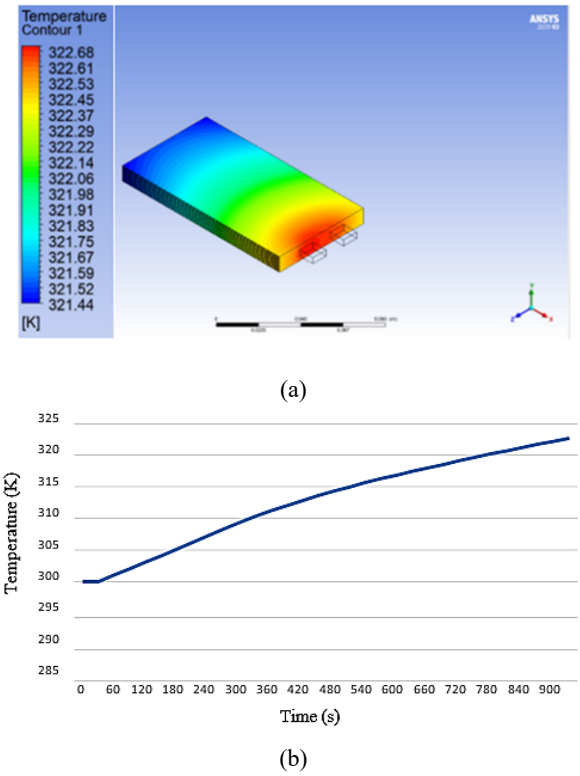


Figure 2. (a) Battery Contour Without Cooling Plate (b) Maximum Temperature Graph of Lithium-Ion Battery Without Cooling Plate.

B. Cooling Fluids Performance Temperature Distributions

The temperature distributions on the battery surface were analyzed for each cooling fluid at a mass flow rate of 1×10^{-3} kg/s. Figure 3 presents the temperature contours for water, acetone, ethanol, and methane.

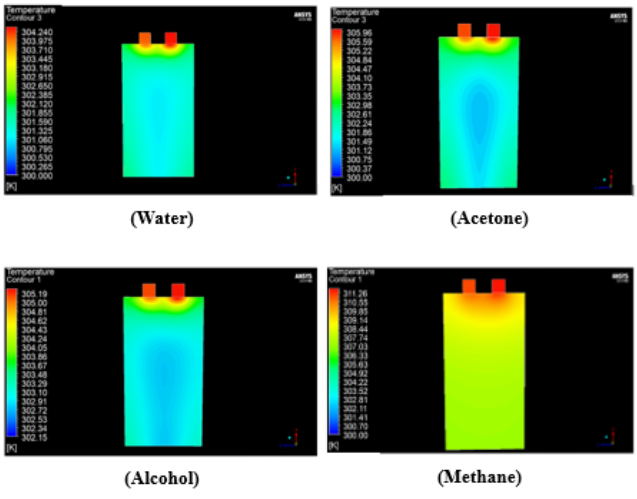


Figure 3. Temperature contours on the battery surface using different cooling fluids at a mass flow rate of 1×10^{3} kg/s.

Figure 3 shows that acetone produced the most uniform temperature distribution and the lowest maximum temperature among the tested fluids, whereas methane resulted in the highest temperature and the poorest uniformity. This outcome is physically consistent with the fluid properties listed in Table 1. Acetone combines relatively low viscosity with moderate thermal conductivity, which

increases the Reynolds number at a given mass flow rate and supports a higher convective heat-transfer coefficient. In contrast, methane has very low density and very low thermal conductivity, limiting its ability to absorb and transport heat from the battery surface.

The maximum battery temperatures and average heat transfer coefficients for each fluid are summarized in Table 2.

Table 2. Maximum battery temperatures and average heat transfer coefficients for different cooling fluids at 1×10^{3} kg/s.

Fluid	Maximum Battery Temperature (°C)	Average Heat Transfer Coefficient (W/m²·K)
Water	28.9	2500
Acetone	28.0	2700
Ethanol	28.8	2400
Methane	36.8	800

Acetone achieved the lowest maximum battery temperature of 28.0 °C, closely followed by water and ethanol. Methane's maximum temperature was significantly higher at 36.8 °C, indicating inadequate cooling performance.

The superior performance of acetone can be attributed to its favorable thermal properties, specifically its relatively high thermal conductivity and low viscosity, which enhance convective heat transfer. Despite water's higher thermal conductivity, acetone's lower viscosity results in a higher Reynolds number, promoting better turbulence and heat transfer within the mini-channels.

Methane, with its low density and thermal conductivity, was unable to effectively remove heat from the battery surface. These findings align with previous studies that emphasize the importance of thermal conductivity and specific heat capacity in cooling fluids for battery thermal management [6].

C. Effect of Mass Flow Rates on Battery Temperature

The effect of mass flow rate on the maximum battery temperature was evaluated for each cooling fluid. Figure 4 illustrates the relationship between mass flow rate and maximum battery temperature.

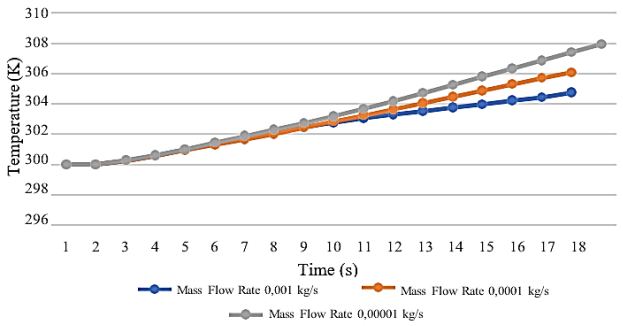


Figure 4. Maximum battery temperature versus mass flow rate for different cooling fluids.

An increase in mass flow rate from 1×10^{-5} kg/s to 1×10^{-3} kg/s resulted in a significant reduction in maximum battery temperature for all fluids. For example, using water as the cooling fluid, the maximum temperature decreased from 34.5 °C at 1×10^{-5} kg/s to 28.9 °C at 1×10^{-3} kg/s.

The pumping power required for each mass flow rate was calculated using the following equation :

$$P_{pump} = \frac{\Delta P \times \dot{V}}{\eta} \quad (3)$$

where ΔP is the pressure drop across the cooling channels, $\dot{V}$ is the volumetric flow rate, η is the pump efficiency, assumed to be 70%.

Table 3. Pumping power required for water at varying mass flow rates.

Mass flow rate (kg/s)	Pressure drops (Pa)	Pumping power (W)
1×10^{-5}	500	0.01
1×10^{-4}	2000	0.29
1×10^{-3}	8000	4.11

The results indicate that higher mass flow rates significantly increase the pumping power required, which could impact the overall energy efficiency of the system.

Balancing cooling efficiency and energy consumption is crucial. The mass flow rate of 1×10^{-4} kg/s offers a compromise, providing adequate cooling while keeping the pumping power at a moderate level.

D. Influence of Geometric Enhancements

The impact of geometric enhancements on temperature uniformity was assessed by comparing the baseline design (straight channels) with designs featuring staggered fins and variable cross-sections. Figure 5 shows the temperature distributions for each configuration using acetone at a mass flow rate of 1×10^{-3} kg/s.

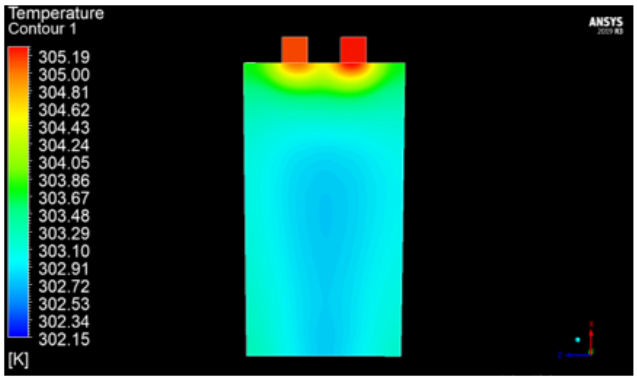


Figure 5. Temperature distributions for different channel geometries using acetone at 1×10^{-3} kg/s.

The inclusion of staggered fins improved temperature uniformity, reducing the temperature difference across the battery surface by approximately 15%. Variable cross-sections further enhanced uniformity, achieving a 20% reduction compared to the baseline.

Geometric enhancements affected the pressure drop within the cooling channels. Table 4 presents the pressure drops for each configuration.

Table 4. Pressure drops for different channel geometries using acetone at 1×10^{3} kg/s

Geometry	Pressure Drop (Pa)
Straight Channels	8000
Staggered Fins	9500
Variable Cross-Section	11000

While the enhanced geometries improved cooling performance, they also increased the pressure drop, requiring more pumping power.

The overall performance improvement was quantified by considering both the reduction in maximum battery temperature and the increase in pumping power. The staggered fin design reduced the maximum temperature by 0.8 °C compared to the baseline, with a 19% increase in pumping power. The variable cross-section design achieved a 1.2 °C reduction but required a 38% increase in pumping power.

E. Environmental and Safety Assessments

An environmental assessment was conducted to evaluate the potential impact of each cooling fluid. Acetone and ethanol, while effective as cooling fluids, are volatile organic compounds (VOCs) with potential environmental and health risks [8]. Water is environmentally benign but may present issues related to corrosion and electrical conductivity if leaks occur. Methane, being a greenhouse gas, poses significant environmental concerns if released into the atmosphere.

The safety risks associated with each fluid were evaluated based on flammability, toxicity, and handling requirements. Acetone and ethanol are highly flammable, requiring strict safety protocols. Methane is also flammable and poses asphyxiation risks in enclosed spaces. Water is the safest option in terms of flammability and toxicity but may not provide the same level of cooling performance as acetone. Table 5. summarizes the safety and environmental considerations for each fluid. Table 5 summarizes the safety and environmental considerations for each fluid.

Table 5. Safety and environmental considerations of the cooling fluids.

Fluid	Flammability	Toxicity	Environmental Impact
Water	Non-flammable	Non-toxic	Minimal
Acetone	Highly flammable	Low	Moderate (VOC)
Ethanol	Highly flammable	Low	Moderate (VOC)
Methane	Flammable	Low	High (Greenhouse Gas)

F. Statistical Validation

Statistical analysis was performed to determine the significance of the differences observed between the cooling fluids and geometries. An analysis of variance (ANOVA) test confirmed that the variations in maximum battery temperatures due to different cooling fluids were statistically significant ($p < 0.01$). Similarly, the impact of geometric enhancements on temperature uniformity was significant ($p < 0.05$). Figure 6. illustrates the confidence intervals for maximum battery temperatures with different cooling fluids. Figure 6 illustrates the confidence intervals for maximum battery temperatures with different cooling fluids.

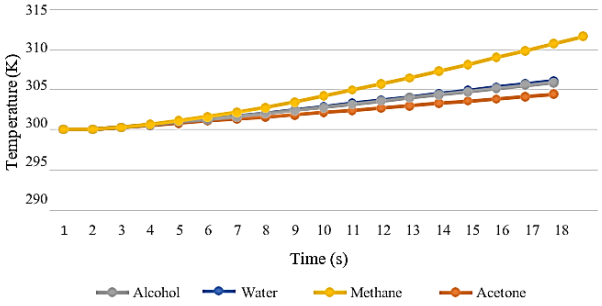


Figure 6. Confidence intervals for maximum battery temperatures using different cooling fluids.

The narrow confidence intervals indicate a high degree of reliability in the results. The statistical validation supports the conclusion that both the choice of cooling fluid and the geometric design of the mini-channel cold plate significantly affect the thermal performance of the battery cooling system.

Discussion

The present study investigated the thermal management of lithium-ion (Li-ion) batteries using a mini-channel cold plate system, focusing on the effects of cooling fluid selection, mass flow rate variations, and geometric enhancements on cooling performance. The findings provide valuable insights into optimizing battery cooling systems to improve efficiency and safety in electric vehicle (EV) applications.

A. Interpretation of Findings

Cooling Fluid Selection

The results demonstrated that acetone outperformed water, ethanol, and methane in reducing the maximum battery temperature and enhancing temperature uniformity. Acetone achieved the lowest maximum battery temperature of 28.0 °C at a mass flow rate of 1×10^{-3} kg/s, attributed to its favorable thermal properties, including relatively high thermal conductivity and low viscosity. These properties enhance convective heat transfer by increasing the Reynolds number and promoting better fluid flow within the mini-channels.

Water, although having higher thermal conductivity than acetone, exhibited slightly inferior cooling performance due to its higher viscosity, which may reduce flow rates and turbulence levels under the same pumping power. Methane showed significantly poorer performance, with a maximum battery temperature of 36.8 °C, owing to its low thermal conductivity and density, which limit its capacity to absorb and transport heat effectively.

The superior performance of acetone aligns with previous research emphasizing the importance of selecting cooling fluids with high thermal conductivity and appropriate viscosity for efficient thermal management [6]. However, the flammability and environmental concerns associated with

acetone necessitate careful consideration for practical applications.

Impact of Mass Flow Rate

Increasing the mass flow rate substantially improved the cooling efficiency across all tested fluids. Higher mass flow rates enhanced convective heat transfer coefficients, reduced thermal resistance, and minimized temperature gradients on the battery surface. For instance, increasing the mass flow rate of water from $1\times10-5$ kg/s to $1\times10-3$ kg/s reduced the maximum battery temperature from 34.5 °C to 28.9 °C.

These findings corroborate previous studies that have identified mass flow rate as a critical factor influencing cooling performance in battery thermal management systems [4], [9]. However, the increased mass flow rates also led to higher pressure drops and pumping power requirements, impacting the system's overall energy efficiency. Therefore, optimizing the mass flow rate involves balancing cooling performance with energy consumption considerations.

B. Comparison with Previous Studies

The findings of this study are consistent with earlier research emphasizing the importance of optimizing cooling fluid properties, flow rates, and channel geometries for effective battery thermal management. Hussein et al. [6] highlighted the potential of fluids with enhanced thermal conductivity and appropriate viscosity in improving heat transfer rates. Similarly, Wang et al. [4] demonstrated that increasing the coolant flow rate enhances cooling performance but also increases energy consumption due to higher pumping requirements.

The geometric enhancements explored in this study align with the work of Ma et al. [11*], who investigated the use of fins and other turbulence-promoting features to improve heat transfer in mini-channel systems. The observed improvements in temperature uniformity and reduction in thermal hotspots are critical for preventing localized overheating and extending battery life.

C. Practical Implications

Safety and Environmental Considerations

While acetone exhibited superior cooling performance, its high flammability and volatility pose significant safety risks. The use of acetone in EV battery cooling systems would require stringent safety measures, including leak detection, proper ventilation, and the use of explosion-proof equipment. Additionally, acetone is classified as a volatile organic compound (VOC), contributing to environmental pollution if not managed properly [8].

Water, being non-flammable and non-toxic, presents a safer alternative despite its slightly lower cooling performance. Ethanol shares similar safety concerns with acetone due to its flammability. Methane, although less effective as a coolant, poses substantial environmental risks as a potent greenhouse gas if released into the atmosphere.

Alternative Cooling Fluids and Energy Efficiency

Given the safety and environmental challenges associated with acetone and ethanol, exploring alternative cooling fluids is essential. Nanofluids, which are engineered colloidal suspensions of nanoparticles in base fluids, offer enhanced thermal properties while potentially mitigating safety risks [12]. Nanofluids based on water with additives like copper oxide (CuO) or aluminum oxide (Al_2O_3) nanoparticles have demonstrated increased thermal conductivity and heat transfer capabilities [13]. Bio-based coolants derived from environmentally friendly materials could also be viable options, combining effective thermal management with reduced environmental impact.

The increased pumping power required at higher mass flow rates and with geometric enhancements raises concerns about the overall energy efficiency of the cooling system. In practical applications, the energy consumed by the cooling system should not offset the benefits gained from improved battery performance. System designers must optimize the cooling system to achieve the desired thermal performance with minimal additional energy consumption.

Scalability and Application in EVs

Scaling the mini-channel cold plate system for use in full-scale EV battery packs presents additional challenges. The complexity of the cooling system increases with the number of battery cells, and ensuring uniform cooling across all cells becomes more difficult. Modular cooling designs and the integration of thermal management systems with battery management systems (BMS) could help address these challenges [14].

D. Limitations of the Study

Several limitations should be acknowledged. First, the study focused on a limited number of cooling fluids and did not explore advanced coolants like nanofluids or bio-based fluids, which may offer improved performance and safety profiles. Second, the simulations and experiments were conducted under steady-state conditions, whereas batteries in real-world applications experience dynamic operating conditions with fluctuating thermal loads. Third, the study did not consider the long-term effects of coolant-material interactions, such as corrosion or degradation of materials, which could impact the durability of the cooling system.

E. Recommendations for Future Research

Future studies should explore a broader range of cooling fluids, including nanofluids and environmentally friendly alternatives, to identify optimal solutions that balance performance, safety, and sustainability. Investigating the thermal performance of the cooling system under transient conditions would provide a more accurate representation of real-world battery usage. Additionally, research into the long-term reliability of the cooling system components and materials, as well as the development of advanced control strategies for thermal management, would further enhance the applicability of these systems in EVs.

Exploring hybrid cooling approaches that combine liquid

cooling with phase change materials (PCMs) or heat pipes could offer improved thermal regulation while mitigating some of the drawbacks associated with increased pumping power and complex geometries [16]. Integration of the cooling system design with the overall battery pack architecture and vehicle thermal management systems is also essential for optimizing performance at the system level.

F. Economic Considerations and Environmental Impact

The economic feasibility of implementing advanced cooling fluids should be evaluated. Alternative cooling fluids may have higher material costs or require specialized handling and equipment. Cost-benefit analyses are necessary to determine the viability of these solutions in commercial EV applications.

The environmental assessment highlighted the need to consider the ecological footprint of cooling fluids and system designs. Transitioning to sustainable cooling solutions aligns with global efforts to reduce environmental impact and supports the broader adoption of EVs as environmentally friendly transportation options. Future research should include comprehensive life cycle assessments of cooling systems to quantify their environmental benefits and trade-offs.

Conclusion

This study examined the thermal management of lithium-ion (Li-ion) batteries using a mini-channel cold plate system, focusing on cooling fluid selection, mass flow rate variations, and geometric enhancements. Acetone outperformed water, ethanol, and methane as a cooling fluid, achieving a minimum battery temperature of 28.0°C at a 1×10^{-3} kg/s flow rate due to its high thermal conductivity and low viscosity, though its safety and environmental risks require careful consideration. Increasing the mass flow rate improved cooling efficiency by enhancing convective heat transfer and reducing thermal resistance, though it also increased pressure drops and energy demands. By optimizing the selection of cooling fluids and mass flow rates, it is possible to enhance battery performance, extend lifespan, and mitigate safety risks associated with overheating.

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References

[1] T. M. Bandhauer, S. Garimella, and T. F. Fuller, "A Critical Review of Thermal Issues in Lithium-Ion Batteries," *J. Electrochem. Soc.*, vol. 158, no. 3, p. R1, Jan. 2011, doi: 10.1149/1.3515880.

[2] R. Spotnitz and J. Franklin, "Abuse behavior of high-power, lithium-ion cells," *J. Power Sources*, vol. 113, no. 1, pp. 81–100, Jan. 2003, doi: 10.1016/S0378-7753(02)00488-3.

[3] J. Zhao, Z. Rao, and Y. Li, "Thermal performance of mini-channel liquid cooled cylinder based battery thermal management for cylindrical lithium-ion power battery," *Energy Convers. Manag.*, vol. 103, pp.157165,Oct.2015,doi:10.1016/j.enconman.2015.06.056.

[4] T. Wang, K. J. Tseng, and J. Zhao, "Development of efficient air-cooling strategies for lithium-ion battery module based on empirical heat source model," *Appl. Therm. Eng.*, vol. 90, pp. 521–529, Nov.2015,doi:10.1016/j.applthermaleng.2015.07.033.

[5] R. Sabbah, R. Kizilel, J. R. Selman, and S. Al-Hallaj, "Active (air-cooled) vs. passive (phase change material) thermal management of high power lithium-ion packs: Limitation of temperature rise and uniformity of temperature distribution," *Sel. Pap. Int. Workshop Degrad. Issues Fuel Cells*, vol. 182, no. 2, pp. 630–638, Aug. 2008, doi: 10.1016/j.jpowsour.2008.03.082.

[6] A. M. Hussein, K. V. Sharma, R. A. Bakar, and K. Kadirgama, "A review of forced convection heat transfer enhancement and hydrodynamic characteristics of a nanofluid," *Renew. Sustain. Energy Rev.*, vol. 29, pp. 734–743, Jan. 2014, doi: 10.1016/j.rser.2013.08.014.

[7] W. Yu, D. M. France, S. U. S. Choi, and J. L. Routbort, "Review and assessment of nanofluid technology for transportation and other applications.," ANL/ESD/07-9, 919327, May 2007. doi: 10.2172/919327.

[8] Z. Qian, Y. Li, and Z. Rao, "Thermal performance of lithium-ion battery thermal management system by using mini-channel cooling," *Energy Convers. Manag.*, vol. 126, pp. 622–631, Oct. 2016, doi: 10.1016/j.enconman.2016.08.063.

[9] US Department of Health and Human Services, "Agency for Toxic Substances and Disease Registry-ATSDR.," 1999.

[10] A. A. Yaqien, M. Yamin, and C. P. Mahandari, "Sistem Manajemen Termal Baterai LiFePO4 Menggunakan Pelat Pendingin Mini Channel untuk Aplikasi Kendaraan Listrik," JST (Jurnal Sains dan Teknologi), vol. 12, no. 3, pp. 779–789, 2024, doi: 10.23887/jstundiksha.v12i3.59241.

[11] M. Li, S. Ma, H. Jin, R. Wang, and Y. Jiang, "Performance analysis of liquid cooling battery thermal management system in different cooling cases," *J. Energy Storage*, vol. 72, p. 108651, Nov. 2023, doi: 10.1016/j.est.2023.108651.

[12] L. Ma, X. Zhao, H. Sun, Q. Wu, and W. Liu, "Experimental Study of Single Phase Flow in a Closed-Loop Cooling System with Integrated Mini-Channel Heat Sink," *Entropy*, vol. 18, no. 6, 2016, doi: 10.3390/e18060128.

[13] R. Saidur, K. Y. Leong, and H. A. Mohammed, "A review on applications and challenges of nanofluids,"

Renew. Sustain. Energy Rev., vol. 15, no. 3, pp. 1646–1668, Apr. 2011, doi: 10.1016/j.rser.2010.11.035.

[14] W. Yu, D. M. France, S. U. S. Choi, and J. L. Routbort, "Review and assessment of nanofluid technology for transportation and other applications.," ANL/ESD/07-9, 919327, May 2007. doi: 10.2172/919327.

[15] H. Park, "A design of air flow configuration for cooling lithium ion battery in hybrid electric vehicles," *J. Power Sources*, vol. 239, pp. 30–36, Oct. 2013, doi: 10.1016/j.jpowsour.2013.03.102.

[16] S. A. 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," *J. Power Sources*, vol. 128, no. 2, pp. 292–307, Apr. 2004, doi: 10.1016/j.jpowsour.2003.09.070.