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Immersion Cooling Techniques: A Review Of Their Potential In Li-Ion Battery Technology

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Abstract: Electric vehicles (EVs) depend heavily on lithium-ion batteries, whose performance and safety are strongly influenced by temperature. As conventional battery thermal management systems, such as air cooling, liquid cooling, phase-change materials, and hybrid approaches, exhibit various limitations, immersion cooling (single-phase and two-phase) has emerged as a highly effective alternative. This review synthesizes findings from twenty research studies to evaluate the capabilities, advantages, and technological progress of immersion cooling for EV battery applications. Both single-phase and two-phase immersion strategies show strong promise, supported by studies on dielectric fluid properties, material compatibility, and system safety. Immersion cooling offers superior thermal control, reduced system complexity, lower infrastructure requirements, and improved environmental performance compared with conventional battery cooling methods. Two-phase systems benefit from latent heat of vaporization for enhanced heat dissipation, while single-phase systems provide stable and cost-effective cooling. Studies highlight that optimized flow designs, reduced cell spacing, splitter-hole configurations, and improved coolant pathways significantly enhance heat removal and temperature uniformity. Even though immersion cooling is a highly viable alternative to existing thermal management systems, the current review emphasizes that continued research is needed to refine non-linear heat transfer modelling, optimize flow-path designs, improve dielectric fluid formulations, ensure long-term material compatibility, and enhance fast-charging safety to fully unlock the potential of immersion cooling in next-generation Li-ion battery systems.

Index Terms – Electric Vehicle, Lithium-Ion, Immersion cooling, Phase change material, battery thermal management systems, dielectric fluid, thermal runaway

I. Introduction

The increasing global demand for fossil fuels and the associated environmental concerns have accelerated the shift toward sustainable transportation solutions. This transition has encouraged the rapid development and adoption of green-energy-based mobility, particularly pure electric vehicles (EVs) and hybrid electric vehicles (HEVs). Many nations are actively promoting these technologies to reduce greenhouse gas emissions, improve air quality, and achieve long-term energy security.

At the core of both EVs and HEVs lies the lithium-ion (Li-ion) battery, valued for its numerous advantages, including high specific energy, high specific power, low self-discharge rate, long cycle life, and superior energy-to-weight ratio. These characteristics make Li-ion batteries the most preferred energy storage system in modern electric transportation. However, the performance, safety, and lifespan of Li-ion batteries are highly sensitive to temperature variations. Their optimal operating temperature typically ranges between 15 °C and 40 °C, and maintaining uniform temperature across cells—ideally with a temperature difference not exceeding 5 °C—is critical. Deviations from these conditions can significantly reduce battery efficiency and accelerate degradation. Excessive heat accumulation may also trigger thermal runaway, posing serious safety hazards.

To address these challenges, effective battery thermal management systems (BTMS) have become essential. A well-designed BTMS helps regulate temperature, enhance performance, improve safety, and extend battery life. As EV demand continues to rise, innovations in cooling techniques, energy-efficient thermal control strategies, and advanced battery materials are becoming increasingly important for ensuring the reliability and sustainability of future electric mobility. To ensure the efficient and safe operating range, the Li-ion batteries are to be worked with an effective cooling technology named battery thermal management systems (BTMS).

Several BTMS technologies—such as active systems (forced-air convection cooling), passive systems (natural convection, heat pipes, and phase change materials), and hybrid systems that integrate both approaches—have been developed to maintain Li-ion batteries within their safe operating temperature range and prevent hazardous thermal runaway. Each of these technologies offers unique advantages: active cooling provides precise temperature control, passive cooling enhances energy efficiency and reliability with minimal power consumption, and hybrid systems deliver improved performance by balancing responsiveness and efficiency.

Air cooling technology is effective for removing low levels of heat, but it becomes insufficient for larger battery packs that demand ultra-fast charging. Liquid cooling offers a significant improvement over air cooling because of its higher specific heat capacity and superior thermal conductivity. Although indirect liquid cooling systems provide good temperature uniformity, favourable heat capacity, and effective thermal control, their increased complexity—due to additional components—introduces potential failure points, adds weight, and raises the risk of coolant leakage. These drawbacks make indirect cooling less suitable for ultra-fast charging applications. Phase change materials (PCMs) present another alternative; however, their low thermal conductivity, reduced dielectric properties, and reliance solely on conduction for solid-phase heat transfer limit their effectiveness in direct cell cooling. As a result, using PCMs alone poses challenges when attempting to meet the high heat dissipation demands of next-generation battery systems.

Immersion cooling is a direct cooling approach that shows strong potential for a wide range of electronic devices and electric vehicle technologies. In this method, the entire battery is submerged in a non-conductive dielectric heat-transfer fluid. To ensure optimal performance, the dielectric fluid must offer a suitable operating temperature range, long service life, good material compatibility, low weight, low viscosity, and strong environmental sustainability. Research efforts have primarily focused on both full and partial immersion cooling techniques, exploring single-phase and two-phase operation under both static and forced flow conditions. Research has identified several promising dielectric cooling fluids for immersion cooling, including hydrofluoroethers, hydrocarbons, esters, silicone oils, and water–glycol mixtures.

The present paper focuses on research-based reviews that explore the potential for widespread adoption of immersion cooling methods in EV technology and Li-ion batteries as a solution to the limitations of current battery thermal management systems. It highlights the growing acceptance of single-phase immersion cooling and examines the feasibility of two-phase immersion cooling, along with innovations such as splitter-hole arrangements and the importance of selecting the most suitable and promising dielectric fluids for effective immersion cooling. Additionally, the paper reviews studies addressing battery degradation issues associated with immersion cooling, including the influence of flow layout, flow type, and flow rate in single-phase systems. It also discusses advancements in passive hybrid immersion cooling, water-based partial immersion methods, mineral-oil-based systems, and manifold-integrated designs. Further topics include experimental investigations of SF33 dielectric fluids, the effects of discharge conditions, optimization of inlet–outlet configurations, and the development of mini-channel and metal-foam-assisted static immersion cooling systems, as well as channel structure design and optimization for improved thermal performance.

The research paper also identifies several future research opportunities related to immersion cooling for Li-ion batteries. These include studying the impact of immersion cooling on the lifetime of various LIB chemistries, understanding performance under low-temperature conditions, and evaluating the long-term material compatibility and stability of immersion-cooled BTMSs. It also emphasizes the need for further safety assessments, investigation of the sustainability of dielectric fluids, and solutions to minimize the large temperature differences often observed between cells. In addition, the paper highlights the importance of developing improved coolant flow-path designs, optimizing flow rates, and creating new dielectric fluids tailored for immersion cooling. It discusses integrating collectors and busbars to reduce temperature non-uniformity, addressing barriers to the widespread adoption of phase-change immersion cooling, and examining coolant aging and bubble behaviour in two-phase systems. Further research directions include cost optimization for hybrid cooling, improving nanofluid stability, advancing evaporative and mist-based cooling methods, implementing wireless IoB-based thermal monitoring, assessing mini-channel and metal-foam-assisted static immersion cooling, and evaluating the practicality of deploying such systems in real vehicles.

II. LITERATURE REVIEW

A) Literature 1:

This paper reveals that Global energy demand continues to rise as most countries rely heavily on the energy sector, accelerating the shift from fossil fuels such as natural gas, petroleum, and coal toward more sustainable technologies like immersion cooling [4]. This research highlights the historical development of immersion cooling—from its origins in the 19th and 20th centuries to major advancements in 2019—and explains how dielectric liquids remove heat through single-phase or two-phase convection systems. Immersion cooling is now used in photovoltaic cells, data servers, crypto-mining, electric vehicle batteries, and power transformers because it improves temperature uniformity, enhances performance, and reduces energy lost as heat. Studies consistently show that immersion cooling is more effective and energy-efficient than traditional methods due to benefits such as lower cost, smaller infrastructure needs, simpler installation and maintenance, environmental friendliness, and stable operating temperatures. Overall, the technology is considered feasible and superior for modern thermal management applications, offering significant advantages across multiple industries.

B) Literature 2:

The research paper depicts the importance of immersion cooling, a rapidly emerging BTMS technology, which submerges battery cells directly in non-conductive dielectric fluids such as hydrocarbon oils, silicone oils, or fluorinated hydrocarbons, enabling uniform heat removal across all cell surfaces and reducing thermal contact resistance compared to indirect systems [2]. Research repeatedly shows that immersion cooling provides superior thermal performance over air and water-glycol cooling, with studies demonstrating lower temperature rise, improved heat transfer coefficients, and enhanced safety due to the flame-retardant nature of many immersion fluids. Although system-level challenges remain—such as fluid cost, material compatibility, added weight, and vapor-condensation requirements—immersion cooling still offers strong potential as an efficient, high-performance solution for modern EV battery packs.

The study also highlighted the merits and demerits of various dielectric fluids. Selecting the right fluid is critical, as it must deliver strong electrical insulation, high specific heat capacity, good thermal conductivity, a high flash point, and sufficient large-scale availability to support EV production. The study consistently examined various types of dielectric fluids and highlighted their merits and demerits. It emphasizes that material compatibility is essential to prevent fluids from degrading plastics, rubbers, seals, or metals in battery modules. Mineral oils are affordable but may cause oxidation and copper corrosion. PAOs are stable, low-toxicity fluids with controllable viscosity, though EV-specific data remains limited. Shell’s GTL-based fluids deliver strong thermal performance and low corrosion risk but can present flammability concerns at lower viscosities. Natural and synthetic esters are biodegradable and have high flash points, yet they can degrade over time, affecting viscosity and cooling efficiency. Silicone oils are dielectric, thermally stable, and effective in low-viscosity forms that improve cooling. Hydrofluoroethers such as 3M Novec offer efficient two-phase cooling but remain costly, harder to dispose of, and denser than other fluid options.

This review examined a range of battery thermal management methods—air cooling, indirect liquid cooling, tab cooling, phase change materials, and immersion cooling—with immersion cooling emerging as one of the most promising approaches due to its direct fluid contact and the high heat capacity of dielectric liquids. The review emphasises that Single-phase immersion cooling is cheaper and simpler than two-phase systems, yet both significantly outperform air cooling. Two-phase immersion cooling further enhances heat removal by using the latent heat of vaporization, helping suppress thermal runaway and homogenize cell temperatures, though its performance is highly temperature-dependent and can decline when vapor films form around cells.

Single-phase and two-phase immersion systems can cool more effectively than air cooling, but issues such as integration challenges, non-linear heat transfer behaviour, and insulating film boiling still need to be addressed. Additionally, for large-scale adoption, research gaps remain in understanding long-term battery life impacts, low-temperature performance, material compatibility, safety behaviour, and the sustainability of dielectric fluids, all of which need to be resolved.

C) Literature 3:

This paper investigates the thermal performance of immersion cooling for an EV battery module using NCA-based 21700 cylindrical lithium-ion cells and compares it with a cold-plate cooling system to evaluate improvements in maximum cell temperature, temperature gradients, cell-to-cell temperature variation, and coolant pressure drop. The present study used a validated 3D time-accurate CFD model in STAR-CCM+, with different discharge rates and coolant flow rates for optimizing the results [3].

The results show that immersion cooling achieves lower maximum cell temperatures and smaller internal temperature gradients at high discharge rates, even though the dielectric fluid's weaker thermal properties lead to greater temperature non-uniformity across the module. However, at low discharge rates, both cooling methods perform similarly, with immersion cooling offering the advantage of a much lower pressure drop.

Temperature patterns show that immersion cooling creates a smooth temperature increase toward the outlet. In contrast, cold-plate cooling transfers heat through copper tubes at the cell bases, leading to hotter spots near the outlet and clusters of higher-temperature cells. The results show that dielectric immersion cooling offers better thermal performance by maintaining lower average and maximum cell temperatures. In cold-plate systems, a large axial temperature gradient develops along the cell length, while immersion cooling produces a radial gradient, demonstrating its superior overall effectiveness. The simpler and cheaper cold-plate system more favourable at low loads, but across all C-rates, cold-plate cooling consistently maintains a much lower cell-to-cell temperature differential than immersion cooling.

The present study shows that immersion cooling results in larger cell-to-cell temperature differences, whereas the aluminum cold plate's serpentine channels distribute heat more evenly and avoid the low-velocity regions that cause hotter cells near the outlet in immersion systems. The current paper also evaluated the influence of coolant flow rate on thermal performance of immersion-cooled and cold-plate-cooled battery modules. As flow rate increases, pressure drop rises nonlinearly in both systems but remains much lower in immersion cooling, while higher flow rates improve convective heat transfer in both methods.

The cold plate shows diminishing benefits at higher flow rates, immersion cooling continues to achieve significantly greater thermal conductance because a much larger portion of the cell surface is directly exposed to the coolant. The study also emphasized that, in addition to its thermal benefits, immersion cooling enhances safety because its dielectric fluid reduces the risk of electrical short circuits during leakage, unlike the conductive water–ethylene glycol mixture used in cold-plate systems. However, immersion cooling also brings challenges, mainly because only a limited range of plastics, rubbers, and seals are compatible with dielectric liquids. The study notes that immersion-cooled modules tend to show larger temperature differences between cells, which is a key concern.

The paper emphasizes that immersion cooling is overall more effective for EV batteries operating at high C-rates or under demanding conditions, though its primary drawback is reduced temperature uniformity. Future studies should explore improved coolant flow-path designs, optimized flow rates, newly developed dielectric fluids, and the integration of collectors and busbars to reduce temperature non-uniformity in current immersion cooling techniques.

D) Literature 4:

This numerical study evaluates immersion cooling performance in a Li-ion battery pack by analyzing different splitter hole arrangements using the chtMultiRegionFoam solver in OpenFOAM® [4].

Two splitter-hole diameters, 2 mm and 3 mm, were evaluated, and the results show that the 2 mm holes provide better cooling because they produce higher fluid velocity and a greater local Reynolds number at the same 4 LPM flow rate, which enhances heat transfer from the cell surfaces. Reducing the number of splitter holes still maintains effective thermal performance with only minor variation, and among the tested designs, Case-3 delivers the best cooling due to the advantages offered by the 2 mm holes.

The research paper highlights the point that among the tested designs, Case-3, which uses row-wise hole reduction, achieves slightly better overall cooling performance than Case-1(uniformly distributed holes) and Case-4(reducing the holes in the column-wise direction) The findings indicate that reducing the number of splitter holes has little effect on the average and maximum cell temperatures, though temperature contours show slightly lower values near the inlet.

Simulations result using the chtMultiRegionFoam solver in OpenFOAM® confirm that 2 mm holes provide better performance than 3 mm holes, making Case-3 the most effective option. Future work may explore phase-change immersion cooling, since earlier studies indicate that boiling heat transfer can further reduce battery temperatures.

E) Literature 5:

This study investigates immersion cooling for a 39-cell (4.6 Ah, 21700 format) 660 Wh battery pack batteries using dielectric fluids such as Ester Mivolt and 3M Novec under 2C, 3C, and 5C discharge rates with coolant flow rates of 2, 4, and 6 LPM. The battery module's geometric model is created in ANSYS Space claim 2023R1, for meshing as well as simulation purpose ANSYS fluent 2023 R1 is used [5].

Based on these findings, Ester Mivolt DF7 is recommended as the more effective dielectric coolant for high-energy-density and high-current Li-ion battery thermal management. The results show that immersion cooling provides effective thermal control, with the highest average cell temperature of 97.50 °C occurring at the 2 LPM–5C condition using 3M Novec, while the lowest average temperature of 29.93 °C occurs at the 6 LPM–2C condition using Ester Mivolt DF7.

Given the safe cutoff temperature of 65 °C for Li-ion cells, higher flow rates are required at 3C and 5C to prevent overheating. Overall, Ester Mivolt DF7 demonstrates superior cooling performance compared with 3M Novec, lowering average cell temperatures by 2.56%, 4.11%, and 12.02% at 2C, 3C, and 5C, respectively, due to its higher specific heat capacity.

These findings confirm that immersion cooling is a simpler and more effective thermal management solution than conventional liquid cooling, reducing the risk of thermal runaway and improving battery reliability. According to the findings of this paper, immersion cooling, is well suited for high power applications as battery pack is submerged in a dielectric fluid, offers up to 10,000 times higher heat-transfer capability compared to passive air cooling. The paper emphasizes, based on the observed thermal behaviour, that the minimum coolant flow rates required for safe operation are 2 LPM at 2C, 2–4 LPM at 3C, and 6 LPM at 5C discharge conditions.

F) Literature 6:

This study presents experimental and theoretical analyses of the thermal and electrochemical effects of immersion cooling on a small module of Li-ion cells [6]. Three hypotheses are proposed and evaluated by comparing experimental results with modelling and simulations. Hypothesis A considers whether reduced radiation heat transfer, caused by fluid coverage lowering emissivity, could elevate internal temperatures and accelerate aging. Hypothesis B examines whether aggressive surface cooling produces steep internal temperature gradients within the jelly roll. Hypothesis C considers the possibility of increased lithium plating at lower surface temperatures, which aligns with EIS evidence indicating plating-related impedance growth.

Overall, the analysis suggests that radiation effects can be ruled out, while internal thermal gradients and lithium plating remain plausible explanations for the increased capacity fade observed under immersion cooling.

The present experimental study, based on EIS analysis, shows that immersion-cooled cells experience about 5% capacity fade, compared to 4.2% in the baseline case. The study indicates that the immersion cooling significantly reduces both surface and core temperatures, in agreement with the theoretical and simulation models developed. However, it also causes a small but measurable increase in capacity fade. Electrochemical Impedance Spectroscopy indicates that the accelerated aging observed under immersion cooling is likely driven by enhanced lithium plating. These findings underscore the importance of considering long-term performance impacts when adopting immersion cooling and provide valuable insight for the design and optimization of electrochemical energy storage systems. The insights gained from this study can support the continued development and practical deployment of immersion cooling strategies that deliver effective thermal management while minimizing long-term electrochemical degradation.

G) Literature 7:

This study integrates experiments and numerical simulations to evaluate electrothermal behaviour of a 280 Ah LFP batteries under constant-power discharge using six commonly used coolants under single phase immersion cooling [7].

The coolants efficiency is compared to assess their effects on cooling efficiency, system stability, and sensitivity to fluid property variation. Additionally, the influence of flow rate and three flow layouts—opposite-side inlet and outlet, same-side inlet and outlet, and jet impingement configuration with coolant introduced at the centre—are analysed to determine the optimal configuration based on temperature control and pressure drop. The jet impingement layout provides the most effective cooling, reducing the maximum temperature by 1.17 °C and the temperature difference by 0.85 °C compared to the opposite-side layout. While the same-side layout creates long circulating flow paths and the opposite-side layout develops low-flow regions, the jet impingement design offers much better temperature uniformity across the surface.

The study analyzed the pressure drop (ΔP), maximum temperature (Tmax), and temperature difference (ΔT) of immersion-cooled batteries using different dielectric fluids. Temperature variation is more significant in the same-side layout, while the jet-impingement layout achieves the most uniform temperature distribution. At higher discharge powers, differences in fluid type and layout become more pronounced. For the same-side layout, flow velocity has the strongest influence on Tmax and ΔT and also helps reduce pressure drop, whereas coolant type has only a minor effect on Tmax. Selecting an appropriate dielectric fluid becomes more challenging at low flow rates.

The study also examined thermal runaway behaviour under single-phase immersion cooling (SPIC) using DF1, triggered by overcharging. The results showed no ignition or explosion, with a peak temperature of 241.9 °C and only smoke release, including H_2, acetylene, and increases in CH_4, C_2H_4, C_2H_6, and CO_2. Overall, the findings emphasize the importance of considering fluid properties and flow-path design, particularly under low-flow conditions relevant to energy storage systems.

H) Literature 8:

The present study reviewed both single-phase and two-phase immersion cooling technologies, assessed the performance of different immersion coolants, and proposed a selection process for choosing the most suitable coolant for battery applications [8]. It also examined the economic feasibility and cost-effectiveness of immersion cooling, and critically analyzed key challenges related to fast charging and discharging, thermal runaway mitigation, nucleate boiling behaviour, coolant–battery interactions, and fluid-flow optimization, along with identifying the associated research gaps.

The paper explains that battery performance is strongly affected by low and high temperatures and compares different BTMS options, noting that air cooling suits only small or hybrid systems, PCM cooling has low thermal conductivity and limited heat rejection, heat-pipe cooling is effective but costly and bulky, and indirect liquid cooling offers better heat dissipation but adds complexity, cost, space demands, and leakage risks—making all three inadequate for high-power fast-changing conditions.

Immersion cooling (IC) provides much better heat-transfer performance than indirect cooling, offering lower thermal resistance, reduced pressure drop, and improved temperature control even at high C-rates. Research demonstrates that full immersion with dielectric fluids such as Novec 7200, transformer oil, and silicone oils can maintain battery temperatures below 30–40 °C, cut temperature rise by over 50%, and decrease pressure drop by up to 92% depending on cell spacing and coolant properties.

Numerical and experimental investigations indicate that optimized flow designs, such as reduced cell gaps, axial or tangential flow, and the use of fins or baffles, greatly enhance heat dissipation and improve thermal uniformity during high-rate charging and discharging.

The present study emphasizes that full immersion cooling offers major thermal benefits over partial immersion and other cooling methods, making it a strong candidate for fast-charging and high-power applications in large battery packs. Comparisons also reveal that full immersion outperforms partial immersion, reducing battery temperatures by up to 20% during high-rate operation. Two-phase immersion cooling (IC) provides significantly enhanced heat dissipation (70% better temperature uniformity and offers superior thermal stability) for high-power batteries by utilizing the latent heat of vaporization to control maximum cell temperatures and improve temperature uniformity.

Dielectric fluids were chosen based on thermal conductivity, heat capacity, viscosity, material compatibility, and environmental impact—key factors that determine cooling performance and safety. Research suggests that viscoelastic fluids can lower pumping power compared with traditional Newtonian dielectric coolants, making them a promising option for fast-charging battery systems. Hydrocarbon-based fluids.

The study also highlighted the merits and demerits of various dielectric fluid such as Fluorocarbons, Esters, Hydrofluoroolefins (HFOs)allowing precise battery temperature control during fast charging) and Silicone oils (more reliable). The present research paper highlighted the meroits of immersion cooling such as 27% cost reduction and 25% lower carbon footprint, direct heat removal, reduced thermal resistance, suppression of thermal runaway, and prevention of fire propagation by dissolving flammable gases. More research on coolant aging and bubble behavior in two-phase immersion cooling is essential for its widespread adoption and for establishing it as a mainstream BTMS solution in future EVs.

I) Literature 9:

This study investigates a hybrid thermal management system for light electric vehicles that combines dielectric immersion cooling, heat pipes, and fins to regulate lithium-ion battery temperatures. Four dielectric oils are tested and compared with air and deionised water using a 3D Ansys model of a 4S4P NMC battery pack under a 2C discharge [9]. Buoyancy improves cooling by roughly 20%, especially for more viscous fluids. The system performs well at low to moderate heat loads, but at very high heat generation (up to 100 kW/m³), battery temperatures can exceed 90°C, showing system limits. Enhancing heat sink and insulation properties significantly reduces temperatures, and the best design uses larger heat pipes with five evenly spaced fins. Overall, the hybrid TMS improves battery safety, performance, and lifespan for compact EVs.

This research evaluates a new passive hybrid battery cooling system—combining dielectric immersion cooling, heat pipes, and fin configurations—for electric two-wheelers using numerical analysis of non-circulating fluid prototypes. The study highlights that the hybrid cooling system provides significantly better battery temperature control than air cooling, lowering both peak temperatures and thermal gradients to reduce hotspot formation. Using a thicker dielectric fluid enhances buoyancy-driven cooling and can decrease battery temperatures by up to about 10 °C. The system performs exceptionally well under low to moderate heat generation (1–50 kW/m³), but its effectiveness declines at very high loads (100 kW/m³), where temperatures may exceed 91 °C, indicating that supplementary cooling could be necessary under extreme conditions. Among the configurations tested, the design featuring five evenly spaced fins combined with an appropriately sized heat pipe delivered the best thermal performance without adding excessive weight

.The configuration with 5 evenly distributed fins provides the minimum battery maximum temperature ($Tmax$) of 89.22 °C and temperature disuniformity (ΔT) of 2.45 °C compared to all configurations. The heat pipes diameter do no affect the performance. When buoyancy effects are included, deionised water and the two Cargill dielectric oils perform best because their high specific heat capacity and relatively low viscosity give them a high Rayleigh number, making them more effective at natural convection. The comprehensive study reveals that the present hybrid TMS provides a compact, efficient solution for light EVs, enhancing battery safety, performance, and lifespan during demanding operation.

J) Literature 10:

The present paper indicates that immersion cooling is effective for lithium-ion batteries, but dielectric fluids are expensive and water cannot be used directly because it is not electrically insulating [10]. Near full-depth partial immersion (NFDPI) offers a solution by allowing water to cool the cells without touching the tabs. Experiments and simulations show that NFDPI controls battery temperature well, with remaining temperature differences mainly caused by vertical gradients in the cells. This study evaluates a water-based NFDPI thermal management approach, where the immersion depth is controlled to keep water away from the battery tabs.

An experimental setup is built to assess how coolant flow rate, discharge rate, and inlet–outlet configuration affects the module's peak temperature and temperature uniformity, supported by numerical simulations of the coolant flow. The findings offer practical guidance for designing and optimising water-based partial immersion cooling systems for lithium-ion battery energy storage.

The present study demonstrates the system's superior cooling capability, achieved through natural convection and static immersion, which result in lower peak cell temperatures and improved temperature uniformity. At a 1C discharge rate, increasing the coolant flow enhances convective heat transfer, reducing both the average temperature and the end-of-discharge maximum temperature. The NFDPI system maintains effective thermal control up to 1.5C. However, at 2C, although the maximum temperature remains relatively low (36.75 °C), the temperature gradient increases to 8.01 °C, exceeding safe operational limits.

K) Literature 11:

Many studies have emphasized the potential of immersion cooling through simulations, yet experimental validation and a clear theoretical understanding of its heat-transfer mechanisms remain limited [11]. In this work, the fresh 18650-type LIB (SAMSUNG) is used for experimentation. This work performs controlled experiments under both static and flowing conditions using a model-scale battery system immersed in mineral oil to assess its thermal performance. The results show that battery temperatures remain below 35 °C at a flow rate of 5 mL/min and drop below 30 °C when the flow exceeds 15 mL/min, even at a high 4C discharge rate. While increasing oil flow enhances cooling, the improvement diminishes as the system approaches its maximum heat-removal capacity.

Theoretical analysis indicates that the dominant heat-transfer mechanism varies with both the discharge rate and the fluid Reynolds number, with natural convection becoming the primary mode at higher cycling rates. Overall, the study provides both quantitative and theoretical evidence supporting the effectiveness of mineral-oil immersion cooling and offers valuable insights for the design of practical immersion-cooling systems.

L) Literature 12:

Inspired by manifold microchannel (MMC) cooling used in electronics, the present study proposes a novel manifold immersion (MI) cooling structure for battery packs and evaluates its performance through numerical simulations [12]. The analysis shows that, unlike traditional MMC designs, MI cooling requires strong heat transfer mainly along the lateral battery surfaces rather than the bottom or baffle areas.

Key design parameters—especially manifold channel length (Lch,m) and battery-spacing channel width (Wch)—strongly affect performance. Stable wall-jet flows, which form when Lch,m or Wch is sufficiently large, improve cooling by reducing vortex regions and enhancing temperature uniformity.

With optimized parameters, the MI system limits the maximum battery temperature to 35.06 °C at 5C discharge, achieving bulk and surface temperature non-uniformities of 6.66 °C and 3.52 °C, respectively.

The MI cooling method introduced in this study integrates immersion cooling with forced convection, creating a system that avoids the need for additional heat sinks by shaping the coolant flow according to the natural geometry of prismatic lithium-ion batteries.
This design ensures high cooling capacity and excellent temperature uniformity while simplifying manufacturing and enabling more compact battery pack configurations. The advantages of the approach is depicted through the analysis of thermal behaviour and fluid flow patterns within the system, optimizing structural parameters such as manifold channel width, battery spacing, outlet slot width, and baffle height.

Local heat-transfer coefficients are analysed to better understand the mechanisms responsible for the improved cooling performance. The optimized structure is also evaluated across different discharge rates to assess its effectiveness under varying power demands. Although the study focuses mainly on cold environments, heating can be supplied either by an air-based heater or, more efficiently within the MI system, by a liquid heating unit driven by a PTC heater or heat pump. Overall, the MI cooling approach effectively integrates immersion and forced convection, streamlining system design, eliminating local hot spots, and offering a highly promising solution for advanced battery thermal management.

M) Literature 13:

To address the problems of excessive temperature, rise and uneven temperature distribution in battery packs, this study develops a new liquid-immersed battery thermal management system (BTMS) featuring a compact design and high heat-dissipation capability, using five 10-Ah lithium-ion pouch cells connected in parallel [13].
Experimental results show that full immersion (13.2 cm depth) combined with a coolant flow rate of 0.8 L/min provides the best thermal performance under a 2C (100 A) discharge rate at an ambient temperature of 25 °C. Compared with natural air cooling, the maximum cell temperature dropped from 58.3 °C to 39.4 °C—a reduction of 32.4%.
The maximum temperature difference within the module decreased from 4.97 °C to 1.23 °C, representing a 75.3% reduction. This demonstrates that the liquid-immersed BTMS operates efficiently, significantly lowering both the maximum temperature and the temperature difference within the battery module, thereby ensuring more uniform and stable performance. Hence it is an effective solution for thermal management of lithium-ion pouch batteries.
With greater immersion depth and higher coolant flow rates, the system is able to keep the battery temperature within the optimal range of 25 °C to 40 °C, even under high-load conditions.
With the optimal cooling configuration, the BTMS can keep the maximum temperature below 40 °C and limiting the temperature difference to less than 1.5 °C, demonstrating its strong potential for enhancing battery safety, performance, and lifespan.

N) Literature 14:

The problem of battery aging and improve the performance of Li-ion battery, require an effective cooling method to control the temperature [14]. To address this, an experimental investigation using SF33 immersion cooling was conducted, with results validated through Ansys simulations showing temperature deviations within 0.2 °C to 0.6 °C. Additional simulations were performed at a 3 C discharge rate for immersion depths of 25%, 50%, 75%, and 100% of the battery height. A battery pack model was further analyzed under 3C discharge conditions with and without immersion coolant. The immersion cooling system reduced the peak temperature rise by 0.45 °C at 2C and by 1.03 °C at 3C for a single cell. Additionally, the configuration kept the overall temperature near 37 °C with only minimal variation between cells.
These findings confirm that immersion cooling effectively enhances thermal regulation and can substantially contribute to extending the lifespan of Li-ion batteries. The combined experimental and simulation results provide valuable guidance for optimizing the battery system design.

O) Literature 15:

This study critically reviews various battery thermal management systems such as traditional and advanced cooling techniques—including air, liquid, PCM, heat pipe, evaporative, hybrid, mist-spray, and nanofluid systems—highlighting their advantages, limitations, and applications in electric vehicles [15]. The review also pin pointed BTMS classifications, heat transfer mechanisms, and intelligent monitoring technologies using AI, ML, and IoT.

The present paper underscores the need for future research on advanced materials, enhanced heat-dissipation techniques, adaptive cooling strategies, wireless thermal monitoring, and optimized cooling solutions that balance performance, cost, and sustainability to improve the reliability of Li-ion batteries in real-world EV applications.

The study also took initiative to include the performance of hybrid cooling techniques like Integration of PCM with air, liquid, thermoelectric, heat pipe, fins, and nanoparticles. The key challenges and opportunities, AI-, ML-, and IoT-based intelligent algorithms for real-time battery monitoring were discussed.

The study highlights the need for future research on advanced materials, adaptive cooling strategies, and high-efficiency heat-dissipation methods, and further emphasizes that upcoming work should focus on hybrid cooling costs, nanofluid stability, optimized evaporative/mist cooling, and wireless IoB-based thermal monitoring systems.

P) Literature 16:

In this study, fluorinated liquid immersion cooling is investigated as a novel thermal management approach for the Sony VTC6 cylindrical lithium-ion battery—an 18650 cell with a nominal voltage of 3.65 V and a capacity of 3.0 Ah—using SF33 (an engineered hydrofluoroolefin (HFO) fluid produced by Chemours with a boiling point of 33.4 °C) as the immersion fluid. Its performance is compared with forced air cooling (FAC) under 2C, 4C, under rapid discharge and dynamic load conditions, showing that immersion cooling consistently provides superior temperature control [16].

At 4C discharge, FAC results in a 14.06 °C temperature rise, whereas SF33 cooling limits the rise to 4.97 °C. Since the battery temperature closely follows the SF33 temperature, excessively low fluid temperatures should be avoided. The study shows noticeable power losses at SF33 temperatures of 10 °C and 15 °C compared with values above 20 °C. Two-phase boiling heat transfer and bubble dynamics are also analysed, revealing that higher C-rates trigger more intense boiling and stronger cooling. As a result, battery temperature remains below 34.5 °C even during 7C discharge.

Utilizing either single-phase or two-phase mechanisms, the system delivers high cooling efficiency by eliminating thermal contact resistance; even at a 7C discharge rate, the battery temperature remains below 34.5 °C. The effects of different SF33 temperatures on cell temperature and voltage are also examined to guide appropriate coolant temperature selection. High-speed imaging technology is employed to address the limited understanding of boiling and two-phase heat-transfer mechanisms in immersion cooling, enabling direct observation of bubble dynamics and clarification of the underlying heat-transfer processes. Overall, the study highlights the strong potential of liquid immersion cooling and supports the future practical application of SF33-based systems in electric vehicles and energy storage.

The study also finds that excessively low SF33 temperatures (10 °C or 15 °C) lead to noticeable voltage losses at 1C and 2C discharge because of over-cooling. This highlights the need for further research to determine whether immersion systems can provide effective battery heating and thermal retention in cold environments. Additionally, the findings open avenues for future work on bubble detachment frequency and bubble size at higher C-rates, and on evaluating whether these phenomena can help mitigate thermal runaway in lithium-ion batteries.

Q) Literature 17:

This study experimentally examines the thermal management performance of a lithium-ion battery module cooled through direct-contact liquid immersion [17]. Four 2.5 Ah 26650 $LiFePO_4$ cylindrical cells, arranged in a square configuration and connected in parallel, are fully submerged in the dielectric fluid Novec 7000 and their thermal and electrical behaviour is evaluated at charge and discharge rates from 1C to 4C.

Tests are carried out using ambient-temperature fluid for single-phase natural convection and preheated fluid at 33 °C ± 0.5 °C to induce pool boiling for two-phase cooling.

Results show that two-phase immersion cooling provides markedly superior performance at discharge rates of 2C and above, restricting the average temperature rise to just 1.9 °C at 4C discharge and keeping the maximum cell temperature at 34.7 °C. The study also highlights that even during 4C fast charging, the temperature increase is only 1.3 °C, with the maximum temperature remaining at 35 °C. Two-phase cooling also reduces axial temperature gradients within individual cells. The effect of cell spacing is evaluated in this study showing slightly improved heat dissipation and temperature uniformity for the smaller spacing configuration.

R) Literature 18:

This study investigates immersion cooling to improve the thermal management of a 4S2P LIB module operating at a 3 C discharge rate, using the MSMD-NTGK model to evaluate both electrochemical and thermal behavior [18]. Results show that static immersion in ester oil lowers the temperature rise by 8.3% compared to natural air cooling. The study also reveals that forced ester-oil convection achieves temperatures below 5 °C at just 0.077 m/s (20 LPM), outperforming forced air cooling.

The study also examines various inlet–outlet configurations and for ester-oil forced convection, finding that the middle-inlet/middle-outlet center (MIMO-C) design provides the best thermal performance at a reduced flow rate of 5 LPM and a minimal pressure drop of 230 Pa. The results of the present study indicate that immersion cooling is highly suitable for high C-rate charging and discharging. However, further research is needed to evaluate its practical performance and ensure it meets the growing requirements of next-generation e-mobility and energy storage systems.

S) Literature 19:

The current research paper introduces an innovative immersion-based battery thermal management system (BTMS) that integrates mini-channels and metal foam to mitigate the problems of conventional indirect liquid cooling in extreme conditions [19]. The cooling and preheating performance of the system has been improved with the metal foam of high conductivity and structural benefits of mini channels.

The system demonstrated excellent performance under fast-charging conditions, reducing the maximum battery temperature from 50.9 °C to 39.8 °C and lowering the temperature difference to 6.4 K compared with 9.6 K in a conventional forced-immersion system. It also showed strong preheating capability, increasing the minimum battery temperature from 0.6 °C to 11.5 °C within just 10 minutes. Overall, the results indicate that the proposed BTMS provides significant improvements in battery thermal regulation and shows strong potential for electric vehicle applications. Unlike earlier studies that primarily focused on modifying flow paths or inlet/outlet configurations, the present work examines the use of metal foam integrated into a static immersion system. By optimizing the metal-foam properties for both extreme hot and cold conditions, the system achieved a maximum cooling temperature of 39.8 °C, a reduced temperature difference of 5 K, a 56.7% decrease in temperature non-uniformity, and a 22.7% reduction in preheating time. Future research will focus on evaluating the system's performance in real vehicle applications, including its integration into full-vehicle and cabin thermal management systems.

T) Literature 20:

For making effective cooling design essential for battery immersion cooling systems (BICS) this study evaluated four cooling-channel configurations (CC-1 to CC-4). Out of these configurations, CC-1 delivers the best overall performance, offering strong temperature control, good uniformity, and a pressure drop like other designs [20]. For further refining of results of CC-1 configuration, orthogonal optimization and linear weighting analysis were that yields optimal parameters of 4 mm battery spacing, 42 mm baffle height, 14 mm inlet-to-bottom distance, and a 0.04 kg/s coolant flow rate. These improvements reduced the battery pack's maximum temperature and temperature difference by 17.9% and 20.8%, respectively, compared with the unoptimized design. This approach performs far better than air cooling, with studies reporting temperature reductions of about 6 °C and shorter relaxation times between charge–discharge cycles.

The study demonstrates that hybrid immersion cooling designs incorporating heat-transfer materials can further decrease peak temperatures and temperature gradients, improving safety during high-load or abuse scenarios. It also highlights that immersion cooling is especially advantageous for cylindrical LIBs, which are difficult to cool efficiently with indirect liquid cooling because of their curved geometry and poor contact with cooling channels. Static immersion cooling provides faster cooling (50% higher rate) and better uniformity (< 3 K difference at 3C) than forced air cooling.

III. CONCLUSIONS

Electric vehicles play a crucial role in reducing dependence on fossil fuels and lowering air pollution generated by the automotive sector. Their primary energy source—the Li-ion battery—is highly sensitive to environmental temperatures, which can significantly affect performance, safety, and longevity. Therefore, to ensure reliable battery operation and support the continued growth of the EV industry, it is essential to develop efficient battery thermal management systems capable of maintaining optimal temperature conditions and enhancing overall energy efficiency.

A variety of battery thermal management systems—such as air cooling, liquid cooling, phase-change materials, and hybrid cooling—are currently in use, each offering its own advantages and limitations. These shortcomings have motivated the development of a direct cooling approach known as immersion cooling, in which a dielectric coolant is used to fully or partially submerge the battery. Numerous research efforts have been dedicated to advancing partial and full immersion systems, exploring both single-phase and two-phase operation under static or flowing conditions.

The present review examined 20 research studies on immersion cooling, and the key findings are summarized in the following conclusions.

Immersion cooling technology proves to be more effective than many conventional cooling methods, offering benefits such as lower cost, reduced infrastructure needs, simpler system architecture, stable operating performance, and greater environmental friendliness. The review also emphasizes the key properties and capabilities of dielectric fluids, along with the critical importance of ensuring their material compatibility with battery components. Additionally, it highlights the cost-effective single-phase immersion cooling approach, which has been shown to outperform traditional air-cooling systems. The superior latent heat of vaporization in two-phase immersion systems further enhances cooling performance, making them highly effective in mitigating thermal runaway.

A comparative study between immersion cooling and cold-plate cooling technology shows that cold-plate systems are cheaper and perform well under light loads while maintaining a more uniform temperature distribution across cells. In contrast, immersion cooling tends to produce larger temperature differences between cells, though it offers enhanced safety benefits overall and good at high discharge rates.

The numerical study of an immersion cooling system with a splitter-hole arrangement showed that a 2 mm hole provided superior performance due to its higher flow velocity characteristics.

In addition, an evaluation of various dielectric fluids indicated that Ester Mivolt DF7 is the most effective coolant for managing the thermal demands of high-energy-density and high-current Li-ion batteries The average cell temperatures were reduced by 2.56%, 4.11%, and 12.02% at 2C, 3C, and 5C discharge rates, respectively. This improvement is attributed to the fluid's higher specific heat capacity, demonstrating its potential for safe operation and its effectiveness in reducing the risk of thermal runaway. The findings highlight that, based on the observed thermal behaviour, the minimum coolant flow rates required for safe operation are 2 LPM at 2C, 2–4 LPM at 3C, and 6 LPM at 5C discharge conditions.

Although immersion cooling reduces both surface and core temperatures, it can cause a small but measurable increase in capacity fade. The performance of an immersion cooling system is strongly influenced by the flow layout and flow rate. Three configurations—opposite-side inlet and outlet, same-side inlet and outlet, and a jet-impingement design with coolant introduced at the center—were analyzed to identify the optimal setup based on temperature control and pressure drop. Thermal runaway studies further indicate that single-phase immersion cooling with dielectric fluids does not lead to explosions and produces only fumes, demonstrating that this approach is well suited for high-rate discharge conditions and enhances overall operational safety. Numerical and experimental investigations show that optimized flow designs—such as reduced cell gaps, axial or tangential flow, and the addition of fins or baffles—are highly suitable for high-rate charging and discharging conditions.

Full immersion systems are particularly effective for fast-charging and high-power applications in large battery packs. By utilizing the latent heat of vaporization, they achieve up to 70% better heat-dissipation performance and enhanced thermal stability compared to other cooling methods. Static immersion cooling delivers a cooling rate that is 50% faster and achieves better temperature uniformity (less than a 3 K difference at 3C) compared with forced air cooling. Viscoelastic fluids are a promising option for fast-charging battery systems, as they can significantly reduce the required pumping power compared with traditional Newtonian dielectric coolants.

The immersion cooling system with heat pipes, and fin configurations (5 evenly distributed fins)—for electric two-wheelers using numerical analysis gives best results in terms of compactness, battery safety, performance, and lifespan during demanding operation. Near full-depth partial immersion (NFDPI) offers a solution by allowing water to cool the cells without touching the tabs. Experimental results strengthen the potential of using mineral oil as a dielectric fluid for immersion cooling, demonstrating effective performance under both static and flowing conditions.

The manifold immersion cooling approach, which combines immersion with forced convection, streamlines system design, eliminates local hot spots, and offers a highly viable solution for advanced battery thermal management. The immersion cooling system reduced the peak temperature rise by 0.45 °C at 2C and by 1.03 °C at 3C for a single cell, indicating that it effectively enhances thermal regulation and contributes to extending the lifespan of Li-ion batteries. The effect of cell spacing significantly influences the overall performance of the system, as smaller spacing configurations provide improved heat dissipation and better temperature uniformity. The innovative immersion-based battery thermal management system (BTMS) that integrates mini-channels and metal has excellent performance under fast-charging conditions. The findings highlight the strong potential of immersion cooling techniques for addressing fast-charging challenges and mitigating thermal runaway.

In summary, the findings indicate that immersion cooling outperforms all other battery thermal management methods. The paper conclude that the immersion cooling system open numerous opportunities for further research across a wide range of areas such as non-linear heat transfer behaviour, and insulating film boiling, material compatibility, coolant flow-path designs, optimized flow rates, newly developed dielectric fluids, and the integration of collectors and busbars.

Future research should examine whether immersion cooling systems can provide effective battery heating and thermal retention in cold environments. It should also investigate bubble detachment frequency and bubble size at higher C-rates, as well as evaluate whether these phenomena can help mitigate thermal runaway in lithium-ion batteries. The issue of accelerated aging should also be addressed and minimized in future research.

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