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Challenges in Battery Thermal Management for Electric Vehicles: A state-of-the-art review

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Abstract- The rapidly increasing dominance of electric vehicles in automobile industry is leading towards the requirement of an appropriate battery thermal management systems to ensure efficient integration and extended life. This review outlines the battery thermal behaviour and further, how it affects the performance and life of a battery. It has been observed from the study that battery perform optimally within a specified temperature range. There are several factros which triggers the heat generation inside a battery such as fast charging and discharging, high load conditions, unfavourable environmental conditions, etc. Hence, a well planned thermal manangement system is inevitable to prevent runaway accidents and favourable to varied driving patterns. This review compiles for existing active/passive thermal management systems integrated within modern electric vehicles. A special mention is provided on the issues pertaining to the safegty, compatibility, reliability and regulatory compliances. In addition to these, emerging trends and advanced solutions which can answer the aforesaid challenges have also been discussed.

Keywords-- Battery thermal management,electric vehicle, heat generation, thermal runaway, temperature regulation.

1. INTRODUCTION

The transition in automotive sector is striving for a sustainable and ecofriendly solution in form of electric and hybrid vehicles to overcome the ever increasing fuel prices and deteriorating environment. Electric vehicles (EVs) are quite economical mode of transportatio while saving a large amount of green house gas (GHG) emissions. The global approach is much more than this as to reduce the dependency on the other countries to meet their fossil fuel demand and become sustainable. The longterm viability and performance of EVs are much aligned with the new technologies in battery with targets of enhanced driving range and increased vehicle efficiency keeping sustainability into consideration [1].

The battery is the heart of an electric vehicle, supplying the energy required to operate the electric motor and various auxiliary systems. Achieving optimal thermal conditions within the battery is inevitable, as excessive heat generated during charging, discharging, and high load operations can lead to battery degradation. It is not just about performance or efficiency only but also in context of safety risks, including the possibility of thermal runaway [2].

Battery thermal managent is big challenge including limit heat generation and dissipation while ensuring appropriate temperature profiles across each cell, module and packs. The issue become further complex due to vaeried driving and load conditions. The location of battery inside the EV also plays a crucial role in heat dissipation in the battery as most of the EVs are not equipped with proper external cooling system [3, 4].

The first part of this review reports a comprehensive examination of the challenges associated with battery thermal management in EVs. It involves the fundamental principles governing battery thermal behavior and to analyze available thermal control technologies. These include passive and active methods with the help of phase change materials, liquid and air-to compirise of a cooling system, and thermal interface materials. Thereafter, research advancements also discussed to propose innovative solutions to continuing thermal management challenges and offer new opportunities for future developments.

The review concludes by discussing emerging trends that aim to enhance the efficiency, safety and sustainability of EV battery systems [5, 6], along with the role of innovative technologies and availble technological progress in advancing electric mobility [7]. Further, this review underscores the importance of effective battery thermal management in the ongoing success of EVs [8]. As the automotive industry struggles to overcome current technical limitations and transition towards cleaner transportation, addressing battery thermal management challenges remains vital [9]. It also aids a deep understanding of the fundamental thermal behavior of batteries, highlighting recent innovations, and offering promising approaches in thermal management. By analyzing existing knowledge, while identifying research gaps, and proposing future directions, this paper aspires to support further advancements in EV technology and inspire continued innovation in this crucial field.

From the reported literature, it has been identified that battery technology is eveolving and there is a critical comparison is expected to meet the thermal management requirement. Hence, presented literature reports various battery thermal management options while analyzing those on the basis of effectiveness, preparedness and enviro-economic to ensure a compatilility, suitability and sustainability.

2. Battery Thermal Management: Fundamentals and Importance

2.1 Battery Thermal Behavior and Effects

EV batteries are essential components of modern transportation systems, providing an efficient and eco-friendly means of storing and delivering energy. However, their performance, safety, and overall lifespan are heavily dependent on effective battery thermal management. Batter thermal management refers to the process of regulating heat generation, dissipation, and propagation within the battery system installed in EVs [10]. This section underscores details of battery thermal behavior and explains how temperature influences various aspects of battery operation and durability.

During fast charging and discharging cycles, EV batteries undergo electrochemical reactions that generate heat within the cells. As a result, the temperature of the battery increases and may be further affected by ambient temperature and driving conditions [11]. These influences vary with geographical location, season, and time of day, creating diverse thermal environments for the battery.

Temperature plays a decisive role in battery performance. It affects critical parameters, including efficiency, power output, and capacity degradation [12]. Elevated temperatures accelerate the loss of battery capacity, limit the battery's ability to store and supply energy over time. Temperature also impacts internal resistance, which affects power delivery during periods of high demand. Increased internal resistance can lead to reduced power output, slower response, and overall performance decline [13].

Temperature is not just a key performance parameter but also a critical safety concern in battery systems. The thermal behavior of batteries is linked to potential safety risks, highlighting the importance of robust thermal management. Prolonged exposure to elevated temperatures can trigger thermal runaway, which is an uncontrolled, self-sustaining exothermic reaction that may lead to catastrophic battery failure, fire, or explosion [14, 15]. Thermal runaway occurs when the heat generated inside the battery crosses the heat dissipated through cooling, creating a positive feedback loop that further increases temperature. This escalation can cause irreversible structural and material damage, posing serious hazards to vehicle occupants and the environment. In addition to high temperatures, other factors such as overcharging, short circuits, mechanical impact, or exposure to external fire may also initiate thermal runaway [14].

Battery thermal management involves maintaining the battery within an optimal temperature range to ensure safe and efficient operation. Deviating can lead to permanent damage and safety concerns [16]. At low temperatures, battery performance deteriorates due to increased internal resistance and reduced electrolyte conductivity whereas at high temperatures degradation processes escalate and increase the risk of thermal runaway [17, 18].

Table 1: Details of types of batteries used in electric vehicles

Battery Type	**Chemistry**	**Key Features**	**Common EV Usage**
Lithium-ion (Li-ion)	LiCoO$_2$, LiFePO$_4$, NMC, NCA	High energy density, long cycle life, dominant in EVs	Tesla, Nissan Leaf, Hyundai Kona
Lithium Iron Phosphate (LFP)	LiFePO$_4$	Safer, longer life, thermally stable, lower energy density	BYD, some Tesla models
Nickel Manganese Cobalt (NMC)	Li(NiMnCo)O$_2$	Balanced energy, power, and cost	BMW, Chevy Bolt, Kia EV6
Nickel Cobalt Aluminum (NCA)	Li(NiCoAl)O$_2$	High energy density, long life, high cost	Tesla Model S/X
Solid-State Batteries	Solid electrolyte-based	Very high energy density, safer, under development	Next-gen EVs (Toyota, BMW R&D)
Lead-Acid	PbSO$_4$/H$_2$SO$_4$	Low cost, heavy, low energy density	Mostly in hybrids, auxiliary use
Nickel-Metal Hydride (NiMH)	Ni(OH)$_2$/MH	Better than lead-acid, worse than Li-ion, older hybrids	Toyota Prius (earlier models)
Ultracapacitors (Supercapacitors)	-	High power, fast charge/discharge, low energy density	Used in regenerative braking

As discussed earlier, battery thermal management is quite essential to have better heat dissipation, less heat generation and longer battery life which may be achieved by passive and active approaches. Passive approaches do not require external power required to dissipate the heat while active approaches powers air or liquid cooling systems to carry the generated heat from. However, active approaches work quite effectively than the passive but require external source of power to run the mechanism. Therefore, hybrid cooling solutions such as phase change materials (PCMs) are helpful while storing and releasing heat utilizing phase transitions within a narrow operational temperature range. There are many advanced and promising improvements that are expected to make EVs a sustainable mode of transportation by optimizing battery performance, cooling options, and safe ride.

2.2 Role of Thermal Management in EVs

The battery serves as the primary energy source for EVs, powering the traction motor and other vehicle systems. However, battery performance is substantially temperature-dependent and must be maintained within a specific optimal range. Deviations from these either overheating or excessive cooling both negatively impact capacity, power output, and battery life. Effective thermal management prevents these temperature extremes, thereby reducing loss in performance and lifespan caused by chemical and physical changes within the battery structure [19].

Another major benefit of thermal management is improved energy efficiency. Regulating the temperatures of the battery, power electronics, and other heat-generating components prevent energy losses associated with heat dissipation. As an outcome, more stored energy is available for propulsion, extending driving range and reducing the frequency of charging cycles [19].

In addition to this, thermal management also plays a vital role in EV safety and reliability. Elevated battery temperatures can trigger thermal runaway which is a hazardous chain reaction of uncontrolled heat release that may lead to fires or explosions. Thermal runaway results from a positive feedback loop in which rising temperature accelerates exothermic reactions within the battery. Advanced thermal management systems prevent such events by monitoring and regulating cell temperatures [20].

Table 2: Role of thermal management on electric vehicles

Aspect	Role
Significance	Required to propel the EVs keeping thermal equilibrium.
Operational Temperature Range	To ensure long distance coverage keeping battery environment within limit.
Energy Efficiency	Minimizing energy losses, enhanced range and utilization.
Vehicle Architecture	Extends battery usage for auxiliaries and comfort systems.
Mitigating Operational Challenges	Thermal management helps to non-favourable scenarios, preventing overheating and cold-start issues.
Ensuring Safety and Reliability	Prevents thermal runaway events, ensuring vehicle safety and dependability.
Battery Advancement	Advanced battery technologies which can improve round trip efficiency and durable.
Sustainable Solution	Integrating efficient and effective battery cooling techniques for project it as sustainable.

Beyond the battery, thermal management is essential for maintaining the health of inverters and motor controllers. These components experience significant heat during operation and require effective cooling to preserve their performance and durability. Overheating may cause malfunction or failure, compromising safety and vehicle operation. Additionally, thermal management is linked to cabin comfort, as climate control systems highly rely on battery energy to provide heating and cooling for passengers. Efficient temperature regulation in the passenger compartment therefore has a direct impact on driving range and energy consumption [21].

EV performance is influenced by external environmental conditions, including ambient temperature, humidity, and driving conditions. Modern thermal management systems should aim to adapt dynamically to these variations, to ensure component protection while maintaining occupant comfort. As EV technology continues to evolve, thermal management remains an active area for innovation. Research into advanced materials, novel cooling techniques, and intelligent control algorithms projects improvements in component life and system efficiency [22]. Table 2 outlines the various ways thermal management impacts electric vehicle systems.

3. BIBLIOMETRIC ANALYSIS

Reflectors This review uses bibliometric analysis as a quantitative method to evaluate the current state of research in a specific academic area. This technique examines how articles are related through citations and co-citations, resulting in a review that is replicable, systematic, and transparent. The passage explains the use of bibliometric analysis, including bibliometric review and network analysis, as a suitable approach for showing the research trends of a specific field over time [23].

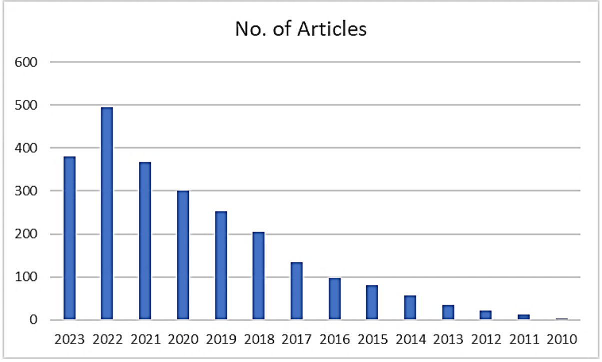

Figure 1: No. of articles published in the field of battery thermal management and electric vehicles

The benefits of bibliometric analysis over traditional methods are discussed, including its objectivity and ability to generate high-quality insights about research development, emerging areas, and key issues affecting a particular research domain. It is compared with traditional methods that depend on subjective literature selection and fixed parameters, which do not effectively capture the evolutionary aspects of research [24]. The data was collected from the Scopus platform. The two main keywords “Battery Thermal Management” AND “Electric Vehicles” were used to search the relevant papers.

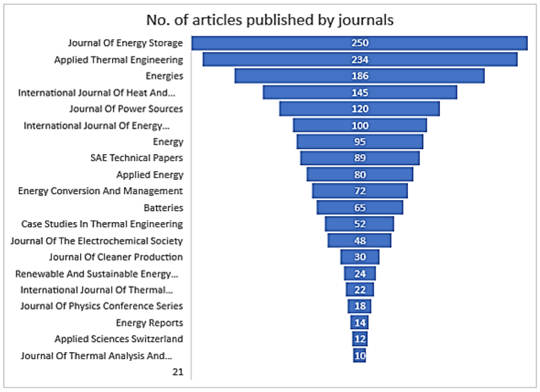

Figure 2: No. of articles published by journals in the field of electric vehicles and battery thermal management systems

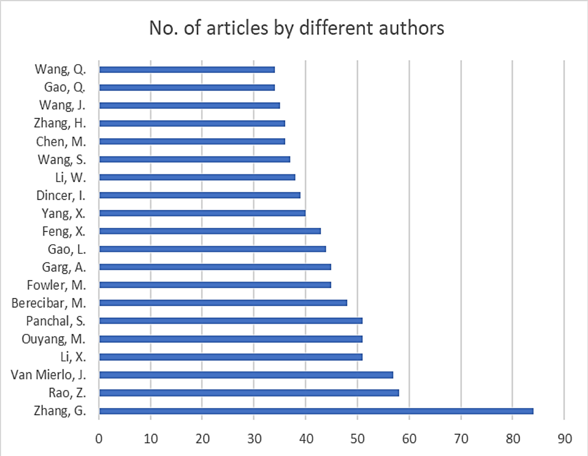

Figure 3: Author wise contribution in the field of electric vehicles and battery thermal management systems

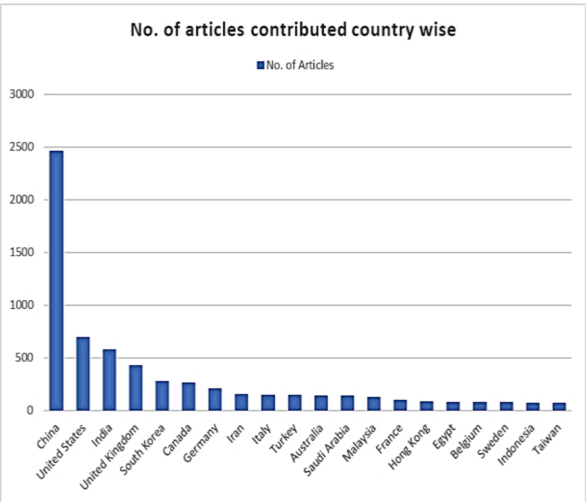

Figure 4: Country wise contribution in the field of electric vehicles and battery thermal management systems

Figure 1 shows the increasing interest in the field of battery thermal management system and electric vehicles. It also shows that the growth is significant in this field in recent years. The distribution of articles in different journals related to this field is shown in figure 2. Journal of energy storage, Applied thermal engineering and Energies are the most popular and preferred journals among authors. Figure 3 shows the authors who have worked extensively in this field. Figure 4 shows the country-wise contribution in this field, and it shows that China is leading the world in the field of electric vehicles and battery thermal management system. After China, the major contributors in this field are United States, India and United Kingdom. Figure 5 shows the network diagram of the keywords used in the articles and the most frequent keywords used were related to lithium-ion batteries and battery thermal management system. This indicates that this is a main area of research interest in the domain of electric vehicles. The analysis reported here in quite helpful in finding the future directions. As in our case, it is clearly indicating the ever increasing research on the compatible advanced cooling options to secure the future of EV industry in form of hybrid cooling techniques, phase change materials, advanced materials for enhanced heat transfer, etc. The technology upgradation in the batteries is the need of hour which can meet the fast charging, range and efficiency at low cost.

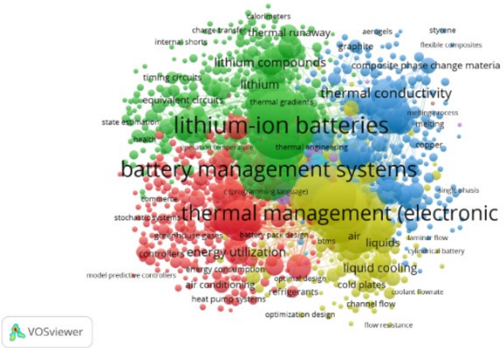

Figure 5: Co-occurrence network of keywords used in articles using VOSviewer.

4. CHALLENGES IN BATTERY THERMAL MANAGEMENT SYSTEM

EV technology faces formidable challenges in the field of battery thermal management. In this section, we examine the complex and diverse issues that require skillful solutions, all in the aim of achieving a balance that ensures high efficiency and safety and reliability in the operation of EV batteries.

4.1 Heat Generation and Dissipation

The battery pack serves as the primary power source in EVs, supplying the electrical energy to generate mechanical motion. However, the energy conversion process is not entirely efficient, as it inevitably produces heat due to internal resistance and the electrochemical reactions occurring within the battery cells. This heat generation is undesirable which can significantly impact battery performance and overall operation [25].

Heat generation and dissipation within the battery pack are critical factors affecting its functionality. The thermal behavior of the battery affects the flow of energy into and out of the cells, governed by fundamental thermodynamic principles. If not managed properly, excessive heat can be generated which inversely affects the battery by reducing its capacity, power output, and altering the optimal operating conditions. Furthermore, developed thermal stress and degradation will compromise long-term performance and durability [26].

Thus, battery operation involves balancing two essential objectives. The first is to use the energy conversion process efficiently, maximizing power delivery which enables greater driving range. The second is to effectively control heat generation and dissipation to prevent excessive thermal buildup, which could lead to safety hazards and irreversible battery damage. Obtaining this balance requires innovative thermal management approaches, and a thorough understanding of battery pack behavior in EVs. Thermal management systems play a crucial role in maintaining the battery pack within a safe and optimal temperature range, ensuring both performance and safety.

4.2 Temperature Regulation and Uniformity

The primary goal of battery thermal management is to maintain an optimum temperature throughout the battery system, which is possible through a comprehensive understanding of cell characteristics and operational patterns in context to dynamic environmental conditions. However, several challenges arise in this process, out of those, thermal imbalances are particularly critical, as they can lead to localized hotspots and escalated degradation in specific cells [27].

These temperature variations can significantly influence the overall performance and lifespan of the battery system. Because the health and function of individual cells are interrelated, the premature overheating of a single cell can reduce its capacity and simultaneously affect the stability and efficiency of the entire battery pack [28].

Ensuring uniform temperature distribution demands sophisticated control systems and well-designed thermal mitigation strategies. In this regard, thermal management algorithms play an essential role. They continuously adapt operating parameters to maintain thermal equilibrium, functioning as the central control hub for cooling systems, insulation layers, and heat dissipation pathways. To address the complexities of thermal distribution, engineers and researchers draw upon multiple scientific disciplines, including fluid dynamics, materials science, and computational modeling. They develop solutions such as adaptive cooling strategies and thermally conductive materials to enhance heat transfer and ensure effective temperature regulation.

Achieving uniform temperature distribution remains a technically demanding task, requiring careful management of thermal behavior and system-level interactions. As electric mobility continues to expand, maintaining thermal balance is a vital step toward precision, efficient, and reliable operation.

4.3 Effect of Operating Conditions

In EV operation, the thermal environment is affected by a wide variety of driving conditions. EVs encounter everything from stop-and-go urban traffic to sustained high-speed cruising on highways, with each scenario presenting distinct power demands and heat generation patterns. The challenge is not only in managing these diverse conditions but also in ensuring smooth transitions between them. The continuous interplay between power demand and heat production requires monitoring and regulation to have thermal stability [29]. Designing such systems requires the capacity to rapidly redistribute heat dissipated in response to the thermal imbalances associated with each driving scenario [30].

Within this framework, battery thermal management has emerged as a key area of technological advancement. Engineers and researchers continue to innovate by developing robust cooling architectures, intelligent control algorithms, and reliable fail-safe mechanisms. Addressing these challenges is essential for unlocking the full potential of electric mobility and contributing to a sustainable transportation future

5. CURRENT STRATEGIES AND TECHNOLOGIES

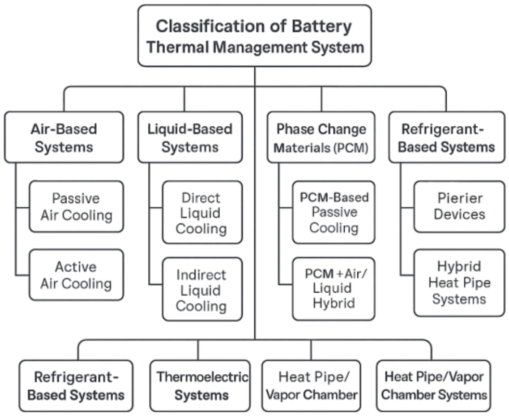

Figure 6: Classification of battery thermal management systems

In the ever-evolving landscape of battery thermal management for electric vehicles (EVs), a diverse array of strategies and technologies emerges in the quest for efficient, safe, and optimal thermal equilibrium. This section discusses these current approaches, each of which is unique in its role in thermal management. Figure 6 shows the classification of battery thermal management systems.

5.1 Passive Thermal Management

Passive thermal management strategies rely on the inherent properties of materials and natural heat transfer mechanisms. These mechanisms leverage the battery's innate capacity to radiate heat, employing heat sinks, heat pipes, and even the vehicle's structural elements to dissipate heat into the surrounding environment. This approach capitalizes on low energy consumption and minimizes complexity. However, its efficacy can be contingent on external factors, such as ambient temperature and driving conditions [31].

5.2 Active Thermal Management

Active thermal management systems proactively intervene to regulate temperature by employing cooling mechanisms and sophisticated control algorithms. Liquid cooling, where a circulation of coolants absorbs and carries away heat, is a common avenue. Active solutions excel in their capacity to adapt to varying thermal demands, ensuring that temperature dynamics remain harmonious under a spectrum of operational scenarios [32].

5.3 Phase Change Materials (PCMs)

Phase Change Materials (PCMs) harness the latent heat absorbed or released during phase transitions, seamlessly absorbing or releasing heat to maintain a steady temperature within the desired range. This thermal metamorphosis ensures that temperature fluctuations are attenuated, enhancing the battery's thermal resilience under a variety of conditions [33].

5.4 Liquid Cooling Systems

Liquid cooling systems circulate a cooling fluid through a network of conduits, adeptly whisking away excess heat. Their modularity allows for fine-tuned control, enabling localized cooling where heat concentration is highest. This precision ensures that the battery's temperature remains within optimal bounds, safeguarding both performance and longevity [34].

5.5 Air Cooling Systems

Air cooling systems embrace simplicity, employing the power of airflow to mitigate heat. Air, guided by strategic pathways and channels, removes heat through convective processes. This approach is pragmatic, relying on natural air circulation while avoiding the complexity of fluid-based systems. While not as precise as liquid cooling, air cooling systems strike a balance between effectiveness and simplicity [35].

From the recent literature, reports various innovative and effective approaches in battery thermal management in form of expanded graphite and metal foam integrated PCM based cooling systems to improve the heat transfer characteristics in EVs [36]. Further, Zhu et al. [37] identified concepts of carbon peak and carbon neutrality as a driving force in the recognition of PCM based hybrid cooling systems for sustainable mode of transport in form of EVs. In another study by Zhu et al. [38] the simulations carried out on PCM integrated with liquid cooling shown approximately 8-8.5% reduction in the power requirements.

Various advanced combinations of passive and active cooling techniques resulting in thermal interface materials, phase change materials, liquid cooling systems, microfluidic cooling, air cooling, etc., works together to obtain thermal equilibrium as shown in Table 3. The objective is to ensure efficient battery operations, safe ride and reliability.

Table 3: Comparison of various battery thermal management techniques

BTMS Type	Temperature Control Range	Heat Dissipation Rate	Efficiency
Passive Thermal Management	Narrow (ambient dependent, ~5–10°C control)	Low	Moderate
Active Thermal Management	Wide (precise control, ±2–5°C)	High	High
Phase Change Materials (PCMs)	Moderate (~10–20°C buffering)	Moderate (latent heat-based)	High (passive + effective)
Liquid Cooling Systems	Very Wide (excellent control, ±1–3°C)	Very High	Very High
Air Cooling Systems	Limited (~5–15°C)	Low–Moderate	Moderate

6. INNOVATIVE APPROACHES AND RESEARCH DIRECTIONS

The ever-evolving era of EVs is only possible through the innovative contributions in the field of battery thermal management. A set of approaches and research directions in the field of EV thermal management is shown in Table 2. The advancement of materials is equally important not only for battery technology development but also for keeping appropriate cooling technology. From advanced cooling techniques that harness the power of phase transitions to sophisticated thermal modeling and simulation tools, and materials innovations with nanomaterials and thermally conductive polymers, these strategies are helpful to transform the way heat in EV battery systems is managed. In addition to these, design of battery pack also serves as an important aspect while selecting appropriate cooling solution for EVs to ensue thermal performance. Table 4 shows various innovative approaches in battery thermal management systems.

In the era of innovation, several advanced approaches are being developed to enhance battery thermal management in electric vehicles. Progress in cooling technologies, thermal modeling, materials engineering, and battery pack design optimization is collectively shaping the future of thermal stability in EV systems. This intersection of science and creativity continues to attract researchers and engineers who are exploring new possibilities and expanding the limits of what can be achieved. As electric mobility evolves, these innovative strategies will play a vital role in improving performance, sustainability, and safety.

Batter thermal management is expected to remain a highly dynamic field characterized by emerging trends and transformative advancements. With the rapid growth of the electric vehicle industry, a convergence of next-generation technologies is anticipated—ushering in new levels of efficiency, safety, and environmental responsibility. A key trend is the integration of artificial intelligence (AI) and machine learning (ML) into thermal management frameworks. These intelligent systems can enable real-time decision-making, adapt to changing operating conditions, and continuously optimize temperature regulation for improved reliability and performance.

Table 4: Innovative approaches and research directions in the field of battery thermal management systems

nnovative Approaches	**Description**	**Perfor mance**	**Cost**
Battery Pack Design Optimization	Innovative pack designs incorporate cooling channels into structural frameworks, ensuring temperature balance and design optimization.	High	High
Advanced Cooling Techniques	Two-phase cooling, utilizing phase transition for enhanced heat transfer efficiency. Utilizing latent heat of vaporization to dissipate heat effectively.	Very High	Low–Moderate
Materials Innovations for Heat Transfer	Nanomaterials, nanofluids, thermally conductive polymers, and composites enhance heat dissipation and redefine thermal management.	High (potential)	Low
Thermal Modelling and Simulation	Computational Fluid Dynamics (CFD) simulations offer insights into temperature distribution, fluid dynamics, and cooling mechanisms, accelerating thermal management development.	Moderate–High (indirect)	Very High

6.1 Industry challenges

The industrial adaption of battery thermal management systems is highly sensitive to operating temperature and safety while keeping the fast charging characteristics in scope. Passive cooling techniques are economical but less effective as compared to active cooling whereas environmental conditions are dominating in selection process along with.

6.2 Commercial EV case studies

The commercial level adoption of advanced liquid cooling techniques has started in form of Tesla Model 3. However, several market players are still following the liquid cooling and air cooling strategies being proved and mature techniques such as Nissan Leaf and Chevrolet Bolt.

7. CONCLUSIONS AND FUTURE SCOPE

The requirement of advanced thermal management is discussed in this review while keeping various aspects of EV technology in tune to offer an optimal and sustainable solution. This review highlighted that battery thermal management is an inevitable system of the electric vehicle ecosystem for improved performance, safety, and sustainable long life. There are many state-of-art concepts such as hybrid cooling using PCMs, microfluidic cooling, advanced IoT integration to monitor issues pertaining to safety and maintenance have been presented. The reported studies here show a great potential of research scope in the advanced cooling techniques and material innovations for enhanced heat transfer in the EV industries. The integration issues of thermal management systems have also been discussed to strengthen the use of EVs as a sustainable mode of transportation with consistency, harmony and reliability. Innovative integration of technology and materials is to be done to ensure safety and efficient operation while meeting the customer requirements in form of fast charging and longer range in future EVs.

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