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A Battery Stacking System for Effective Cooling using Finned Heat Pipe

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ABSTRACT:

One of the challenges that EV vehicles have during operations is proper thermal runaway and battery management system (BMS).

Efficiency of the thermal management system (TMS) while charging and discharging of the lithium-ion battery place a vital role in ensuring the safety and security of the EV vehicles.

The current study focuses on the usage of a heat pipe with fins for effective thermal runaway and protection of the battery stack.

Curved finned Heat pipes in the battery stacking system with increased surface contact will enhance the thermal runaway.

For the suggested battery stacking system with finned heat pipe, thermal runaway simulation analysis is done using CFD tools which records significant reduction in the battery surface temperature.

In addition to enhancing safety, the improved thermal management system with finned heat pipes can also contribute to prolonging the lifespan of the lithium-ion battery.

Keywords: *Battery Management System (BMS), Lithium-Ion Batteries (L-ion batteries), Curved finned Heat pipes, Computational Fluid Dynamics (CFD) tools.*

Introduction

1 Definition: A Battery Thermal Management System (BTMS) is a system designed to regulate the temperature of a battery pack, ensuring it operates within a safe and optimal temperature range. It helps prevent overheating, improves battery performance, extends lifespan, and ensures safety. This is typically achieved using cooling or heating methods, such as air, liquid, or phase-change materials, to maintain the desired temperature range for efficient energy storage and discharge.

2 Working Principle of Thermal management

A computer that is connected to several sensors is the Battery Management System. These sensors transmit data to the BMS about each cell's voltage, current, and temperature. After that, the Battery Management System examines this data to make sure that each cell is operating within the set parameters. If that isn't the case, it tries to resolve the issue.

The BMS controls the cooling system to lower the battery pack's temperature if the cells inside it gets too hot. The Battery Management System balances the cells when there are changes in cell voltage. It transfers energy from one cell to another in order to balance the cells and guarantee that they are all running at the same voltage. The BMS also performs the actions mentioned above and logs the data it collects in order to assess the battery's level of charge and overall health.

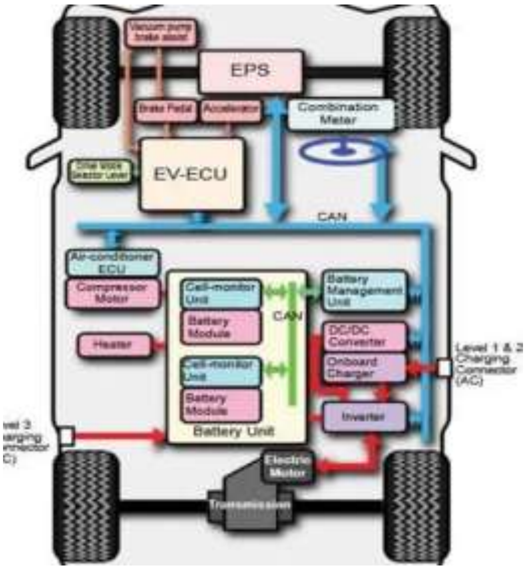

Fig 1. 1 Detailed Sketch of Electrical Vehicle

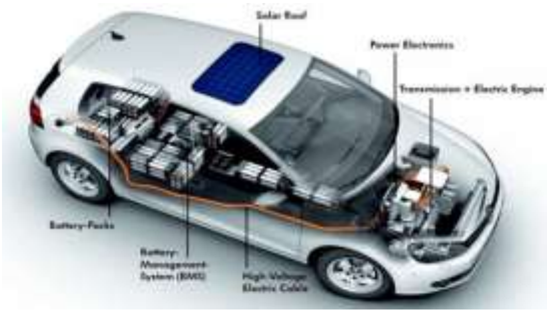

Fig 1. 2 Arrangement of Battery Pack

3. Important operation features of battery thermal management system in electrical vehicles

Temperature Regulation: Keeps the battery pack within an optimal temperature range (usually 20-40°C or 68-104°F) for efficient energy storage and discharge, ensuring peak performance and avoiding thermal degradation.

Active Cooling & Heating: Uses liquid cooling (through coolant circulation), air cooling (via fans), or sometimes even heating elements to prevent overheating during high-power demands (e.g., acceleration, fast charging). Heats the battery in cold weather to maintain optimal performance and reduce energy loss due to lower temperatures.

Thermal Uniformity: Ensures that all cells in the battery pack are at a similar temperature to avoid thermal imbalances, which could lead to reduced performance or uneven wear over time.

Efficient Power Use: Minimizes energy consumption by the thermal management system itself, ensuring that cooling or heating does not drain excess power from the battery, thereby optimizing range and energy efficiency.

Temperature Monitoring: Uses sensors to continuously monitor the temperature of the battery cells and pack. Data is used to adjust the cooling or heating system in real time based on driving conditions, state of charge, and ambient temperature.

Safety and Overheat Protection: Protects the battery from thermal runaway by preventing excessive temperatures, which can lead to fire or damage. If the battery gets too hot, the system will activate cooling measures or shut down certain functions to safeguard the battery.

Fast Charging Support: Ensures the battery stays within optimal temperature limits during fast charging to prevent overheating. Fast charging can generate more heat, so thermal management is crucial to ensure safe and efficient charging speeds.

Regenerative Braking Impact: During regenerative braking (when the vehicle recovers energy), the battery can heat up. The BTMS helps control this by dissipating the heat generated and ensuring that the battery doesn't overheat during these cycles.

Adaptability to Environmental Conditions: The system adapts to varying ambient temperatures (hot summers or cold winters), adjusting cooling or heating strategies to maintain battery health and performance.

Battery Life Extension: By keeping temperatures within the optimal range and reducing thermal stress, the BTMS helps extend the overall lifespan of the battery, reducing degradation and maintaining capacity over time.

4. Types of battery thermal management:

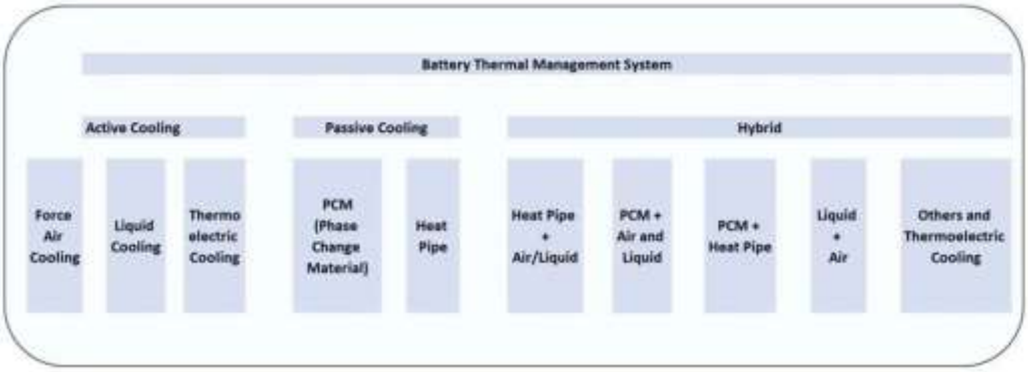

Figure 1.3 Types of Battery management System

Passive cooling: A passive cooling system in a Battery Thermal Management System (BTMS) relies on natural heat dissipation methods without external power sources like pumps or fans. It uses materials such as heat sinks, phase change materials (PCMs), and thermal spreader plates to absorb, distribute, and dissipate heat from the battery. Heat pipes and natural ventilation can also help carry heat away from the battery pack. These systems are energy-efficient, cost-effective, and low-maintenance, but they are less effective in extreme conditions or high-performance scenarios. Passive cooling is typically used in combination with active systems for optimal temperature control in electric vehicles, offering a balance between efficiency and simplicity.

Active cooling system: An Active Cooling System in a Battery Thermal Management System (BTMS) is designed to regulate the temperature of a battery pack by actively removing excess heat, ensuring optimal performance, safety, and longevity. These systems typically use a liquid coolant, which is circulated through the battery pack via pumps, absorbing heat and then releasing it through a heat exchanger or radiator. Fans or compressors may be used to assist in the cooling process. Active cooling is essential in high-power applications, such as electric vehicles, where maintaining a consistent temperature prevents overheating, improves efficiency, and reduces the risk of thermal runaway. While effective, these systems add complexity, weight, and energy consumption, making them more suited for high-performance batteries compared to passive cooling methods, which rely on natural heat dissipation.

Hybrid Cooling System: Hybrid Cooling System in a Battery Thermal Management System (BTMS) combines both active and passive cooling techniques to regulate the temperature of a battery pack. Typically, it uses passive methods like heat sinks, thermal pads, or phase-change materials for initial heat dissipation, while incorporating active elements such as liquid coolant circulation or fans to handle higher heat loads when necessary. This dual approach allows for more efficient thermal management by reducing the reliance on active cooling under normal conditions, thereby saving energy and improving system efficiency. The active components kick in during peak power demands or when temperatures rise beyond a certain threshold. Hybrid systems strike a balance between performance, energy consumption, and complexity, making them ideal for applications like electric vehicles where thermal management must be both efficient and adaptable to varying operating conditions.

5. Properties of Thermal management:

These essential properties are crucial for the effective operation of electric vehicles (EVs) and their associated battery thermal management systems. First and foremost, thermal conductivity plays a vital role in efficiently dissipating heat generated during battery operation, ensuring optimal performance and longevity.

Thermal Conductivity: Materials with high thermal conductivity, such as copper or aluminium, are commonly used for battery cell components and interconnects. These materials help in efficient heat transfer within the battery.

Thermal Resistance: To minimize thermal resistance at interfaces, including between the battery cells and cooling systems, low-resistance materials or thermal interface materials (TIMs) are used. These materials enhance heat transfer.

Specific Heat Capacity: Materials with a high specific heat capacity, such as water-based coolants, are used in cooling systems. They can absorb and store a significant amount of heat while maintaining a relatively stable temperature.

Thermal Insulation: Insulation materials with low thermal conductivity are employed to prevent heat loss or gain from the surroundings. This is especially important in cold or hot climates to maintain the battery's operating temperature within an optimal range.

2. Literature survey

2.1 Gayen, D. et al. [1] examined the safety and temperature management challenges in EV battery systems, focusing on the risks of lithium-ion batteries (LIBs), such as fire and explosion. They identified failure stages, including SEI layer issues, metal dissolution, lithium plating, and separator melting, which could lead to thermal runaway (TR) and fires. The study emphasized the need for improved cooling systems to prevent TR and ensure temperature uniformity across modules. Liquid cooling was found to be the most effective method for heat dissipation and temperature control. Tests on prismatic, pouch, and cylindrical cells revealed that high states of charge (SoC) and mechanical impacts rapidly increased temperatures, triggering TR. The study also supported hybrid cooling systems, combining liquid cooling with phase-change materials (PCM), to lower TR risks and highlighted the importance of standardized control mechanisms for managing thermal behavior and preventing TR spread across battery packs.

2.2 Fayaz, H. et al. [2] studied the impact of extreme temperatures on the performance and lifespan of lithium-ion batteries (LIBs), particularly in applications such as electric vehicles (EVs), hybrid electric vehicles (HEVs), and space environments, where temperatures could drop as low as -120°C. At low temperatures, reduced ionic conductivity and slower chemical reactions led to decreased efficiency. Conversely, rapid charging and discharging caused high internal temperatures, increasing the risk of thermal runaway and potential explosions. The researchers observed that LIBs operated most efficiently between 15°C and 35°C, although they could function within a range of -20°C to 60°C. However, operating outside this range accelerated degradation and heightened the risk of safety hazards, including fires.

2.3 Abdelkareem et al. [3] addressed thermal management challenges in lithium-ion batteries (LiBs) used in hybrid and electric vehicles, where heat buildup from rapid charging and discharging posed risks to performance and safety. They demonstrated that effective thermal management systems (TMS) utilizing heat pipes, phase change materials (PCMs), and nanofluids regulated temperatures and enhanced battery lifespan and efficiency. Experiments with copper-water heat pipes and PCMs achieved maximum cell temperatures of 32.2°C and minimum temperatures of 27.6°C, while exergy efficiency increased by 2.63% to 5.07% under various conditions. Additionally, U-shaped cooling channels, compared to serpentine channels, improved efficiency by reducing pressure drops. The study confirmed that advanced cooling approaches were crucial for optimizing performance and ensuring safety in EV and HEV battery systems.

2.4 Shen, H. et al. [4] explored thermal management in batteries to address heat-induced performance degradation and safety risks. The study focused on a heat pipe-based thermal management system (BTMS) with high thermal conductivity (up to 9216 W/m/K) for efficient heat transfer. Key factors such as battery spacing (D), conduction element thickness (δ), circumference angle (θ), and element height (H) were analyzed. Sensitivity tests revealed that H and θ had the most significant impact on temperature. Increasing δ from 1 mm to 4 mm reduced the maximum temperature from 29.52°C to 29.07°C, but further increasing it to 6 mm raised the temperature to 29.51°C. Expanding θ from 30° to 120° lowered the temperature from 30.30°C to 28.40°C. Computational fluid dynamics (CFD) simulations and experiments confirmed that these adjustments enhanced battery thermal management, thereby improving performance and extending lifespan.

2.5 Bisschop et al. [5] investigated lithium-ion battery (LIB) thermal management using a system that combined phase change materials (PCMs) and heat pipes (HPs) to address overheating and capacity fading risks. Their thermal management module, tested over three charge-discharge cycles, maintained stable battery temperatures at ambient temperatures of 30°C and 35°C. However, at 40°C, the battery temperatures exceeded the PCM melting point (48°C), and at 45°C, the PCM could not fully absorb the heat, resulting in overheating risks. A numerical model closely aligned with experimental data, showing a deviation of just 0.8°C. The study highlighted the effectiveness of combining PCMs for passive cooling and HPs for active cooling, demonstrating improved thermal management in EV applications where precise temperature control is critical for battery safety and longevity.

2.6 Behi, H. et al. [6] studied thermal management strategies for lithium-ion batteries to address overheating during fast charging and discharging. The research compared cooling methods for lithium-titanate (LTO) cells, including natural air cooling, forced fluid cooling, and flat heat pipe-assisted cooling. The results showed that liquid cooling and liquid cooling with heat pipes (LCHP) reduced the maximum battery temperature by 29.9% and 32.6%, respectively, compared to natural air cooling. Increasing the coolant velocity from 0.2 m/s to 1.5 m/s further lowered temperatures from 43.8°C to 37.6°C. Experimental validation confirmed the accuracy of the model, with error rates of 1.2% and 3.2%. The study emphasized the significance of advanced cooling techniques, particularly heat pipes, in enhancing battery performance and safety for high-demand applications such as electric vehicles.

2.7 Hongkun, L. et. al [7] explored the use of oscillating heat pipes (OHP) in battery thermal management systems (BTMS) to address challenges in heat dissipation stability and safety. The study proposed a ⊥-shaped OHP-based liquid-cooling system, focusing on duty cycles, cooling start temperature, and pulsating flow frequency to improve performance stability. Experimental results demonstrated that pulsating flow at 0.03–0.05 Hz enhanced OHP stability, reduced the average battery surface temperature, and improved temperature uniformity. Increasing the cooling start temperature to 45–47°C optimized the system's performance, resulting in a 17.5°C temperature rise, which was a 9.8% reduction compared to non-OHP systems, and a 1.3°C decrease in the maximum temperature differential (ΔT_max). The study underscored the importance of customized thermal management solutions for improving battery safety and performance in high-load scenarios.

2.8 Jose, J., L. et .al [8] focused on optimizing the performance of cylindrical heat pipes (380 mm) for thermal management in electronic components. The study investigated the effects of heat input (10–50 W), cooling water temperature (288.15 K, 293.15 K, 298.15 K), and flow rate (10–40 LPH) on heat pipe efficiency. Eleven K-type thermocouples, with a ±0.5°C error margin, were used to measure temperatures. A neuro-genetic optimization strategy, combining genetic algorithms and artificial neural networks, was employed to identify optimal parameters for minimizing evaporator temperature. Experimental validation demonstrated the method's effectiveness, with a minimal error of 0.66% in the predicted evaporator temperature.

2.9 Zhu, F., et al. [9] addressed challenges in electric vehicle battery thermal management systems (BTMS) during high-rate discharges by proposing a model that incorporated battery heat generation, operating conditions, and flat heat pipe (FHP) structural features. Experimental validation demonstrated that the FHP-based BTMS significantly improved temperature control. In single-cell tests, the maximum temperature difference was maintained below 0.95°C, and the voltage difference was under 0.08V. For battery modules, the maximum temperature difference was 0.57°C, and the voltage difference was 0.05V. The FHP heat transfer model exhibited a 4.61% error under time-varying loads and less than a 1°C difference in steady-state conditions. Simulations and experiments showed a 6.4% reduction in maximum temperature during transient discharges, keeping temperature differences below 2°C, thereby improving battery performance, safety, and lifespan.

2.10 Hendra Yanto et .al [10] explored thermal management for lithium-ion batteries to prevent thermal runaway above 80°C, focusing on Loop Heat Pipes (LHPs) with dual heat sources. Using ethanol (60% fill ratio), a copper evaporator (121 × 56 × 20 mm), and steel battery simulators with cartridge heaters, tests showed that the LHP maintained evaporator temperatures between 50–55°C at high heat loads and under 45°C at lower loads. This dual heat source setup improved thermal uniformity and heat dispersion, ensuring safe temperature control.

2.11 Ruoming et. al [11] addressed insufficient heat dissipation in lithium-ion batteries under high discharge and temperature conditions by proposing a hybrid thermal management system combining micro heat pipe arrays (MHPA) and phase change materials (PCM). The model, verified with minimal deviation (2.3% and 0.18%), reduced the maximum battery temperature to 33.8°C—22.3% lower than air-cooled systems and 7.8% lower than MHPA-only systems. PCMs (RT31, RT35, RT42) achieved temperature reductions of 11.8%, 8.9%, and 5.4%, respectively, under 50 $W \cdot m^{-2} \cdot K^{-1}$ convection. In short-circuit tests, the hybrid system reduced temperature by 12.4% and 29.9% compared to air cooling, thereby enhancing thermal performance, uniformity, and safety with lower power consumption. Further practical comparisons were suggested.

2.12 Chen, K. et al. [12] investigated the performance of lithium-ion batteries during charge-discharge cycles, focusing on the impact of dynamic loading and thermal management. The study highlighted the role of environmental heat transfer coefficients in the effectiveness of the Battery Thermal Management System (BTMS). The average heat generation rate during discharge was found to be 2.7×10^4 Wm^3, while during charging, the heat generation was 5079 Wm^3. The research included five cycles of constant current charge-discharge procedures to demonstrate heat production patterns. However, the study did not account for natural flow effects or volume expansion during Phase Change Material (PCM) operations, and performance was evaluated using two-dimensional simulations. The paper emphasized the importance of managing heat in battery packs, as excessive heat could lead to safety issues for lithium-ion batteries. Additionally, it noted that electric vehicles (EVs) could help mitigate environmental and energy challenges, such as pollution and energy shortages caused by the overuse of coal and oil.

2.13 Sutheesh, P. M. et al.[13] examined the thermal performance of battery designs under dynamic loading using numerical simulations. The study found that battery temperature increased with higher C-rates, meaning faster charge or discharge rates led to greater temperature rises. A hybrid cooling system was effective in reducing both temperature increases and irregularities within the battery. The research also evaluated the effectiveness of Phase Change Materials (PCM) for thermal management, with the melting temperature and latent heat significantly impacting PCM performance. In comparing nanoparticles, Al_2O_3 nanoparticles were shown to outperform CuO nanoparticles in enhancing PCM efficiency. Additionally, the study noted that the density of PCM was the main factor influencing its thermal properties in relation to temperature. However, the model did not consider the effects of radiation heat transfer and assumed that PCM behaved in a homogeneous and isotropic phase.

2.14 Feng, R. et al. [14] investigated a hybrid battery cooling system that combined flat heat pipes and composite phase change materials (CPCMs) to improve temperature regulation. The hybrid system significantly enhanced temperature uniformity and thermal performance, reducing the maximum temperature by 22°C compared to traditional air-cooling systems. The study tested the system under various temperature conditions and developed a lumped thermal model to analyze its performance. The results showed that the hybrid cooling system efficiently managed temperature rise, maintaining a maximum temperature 22°C lower than air cooling, with a temperature increase rate of 2°C per cycle. Additionally, flat heat pipes improved heat dissipation during cycling tests, and the composite PCM-HP system demonstrated superior performance compared to CPCM alone.

2.15 Abd, H. M. et al. [15] explored a new hybrid battery thermal management system (BTMS) that combined phase change materials (PCM) and heat pipes for improved cooling performance. The model demonstrated significant advantages, especially at high discharge rates. Compared to the Air-Model, the maximum working temperature was reduced by 20.1%, and when compared to the pure PCM-Model, the temperature drop was 21.1%. The new system effectively prevented thermal runaway, with the highest temperature not exceeding 48.1°C and a temperature differential of only 1.8°C across the battery. At a 3C discharge rate, the integration of PCM lowered the maximum temperature by 4°C, demonstrating the system's efficient cooling capabilities in maintaining battery safety and performance.

2.16 He, Z., Li, R. et al. [16] Investigated advanced battery heat management solutions, combining micro heat pipe arrays and phase change materials (PCM) to enhance cooling performance. The results showed that the proposed system significantly lowered the maximum battery temperature, reaching 33.8°C, which was 22.3% lower than the maximum temperature of 43.5°C observed in air-cooled systems. The study also compared the effectiveness of different phase change materials—RT31, RT35, and RT42—each resulting in various levels of temperature reduction. The findings highlighted that integrating phase change materials into the cooling system significantly improved thermal performance, providing useful guidance for designing more efficient battery thermal management systems.

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2.18 Butler, C.et al. [18] described a filling rig designed for two-phase cooling devices, which supported both liquid and gas charging, as well as degassing. The rig ensured precise filling volumes, with an average filling capacity difference of 1.7g for liquids and 10.5g for gases. The design was adaptable, allowing customization for different applications. Two-phase cooling devices were noted for efficiently dissipating electronic heat, but prior to fluid charging, internal gases and air had to be evacuated. A benchtop station was developed for vacuum evacuation and fluid charging, supporting both gas and liquid filling configurations. The system achieved accurate filling, with discrepancies between 1.7g and 10.5g, ensuring reliable and precise operation across various use cases.

2.19 Raja et al. [19] studied the lack of charging stations as a significant barrier to electric vehicle (EV) adoption, which caused drivers to experience "range anxiety." The report suggested the need for a robust charging network, as shown in (figure 2.1) improved battery technology, and better temperature control systems to address safety issues like thermal runaway and overheating. The high cost of EVs was also a concern, with the ideal temperature range between 15°C and 45°C being crucial for optimal performance. Efficient cooling systems were also deemed essential for maintaining optimal battery temperature.

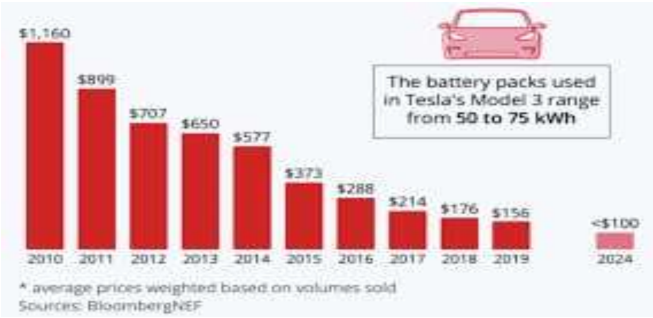

Figure 2.1 Cost of batteries in past decade

2.20 Vidyaandan et al. [20] discussed the limitations of Li-ion batteries for electric vehicles (EVs) and their safety concerns. They highlighted the need for emerging battery technologies and better working conditions. Li-ion cells had a safe working temperature range of 15°C to 50°C, but their life could be significantly reduced below 15°C and above 50°C. Rapid life reduction could lead to thermal runaway, battery failure, and decomposition of electrodes above 180°C. The paper also addressed energy density and cycle life improvements, battery configurations, energy consumption factors, and battery chemistries. It emphasized the importance of safety features in batteries and addressed challenges in battery weight and sizeas shown in (figure 2.2). Comparing different battery configurations helped in selecting the appropriate design for specific applications.

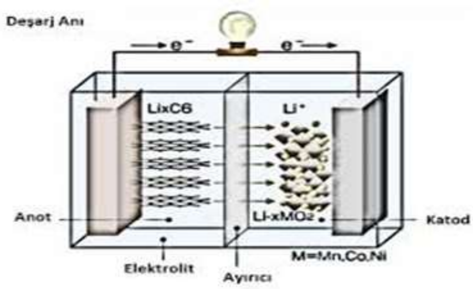

Figure 2.2 Understanding the dynamic of charging and discharging

2.21 Qiu et al. [21] introduced thermal runaway (TR) in lithium-ion batteries as a serious safety concern that could lead to fire and explosion risks. As batteries aged, their temperature stability deteriorated, increasing the possibility of TR. Effective fire separation was deemed crucial in halting the spread of toxic and explosive gases created during TR as shown in (figure 2.3), which posed significant risks. TR gas explosion limits were evaluated experimentally using tests such as Chen's FRTA device for gas LEL and Karp's incendiary bomb for flammability. Explosion limits were determined using the L-C method as shown in (figure 2.4).

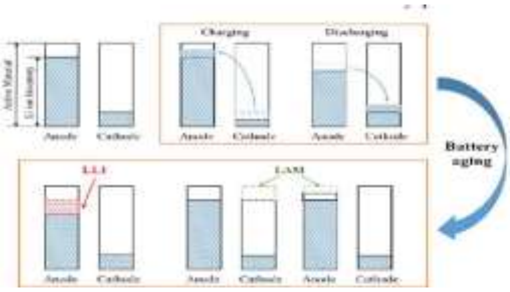

Figure 2.3 Dual Tank Model

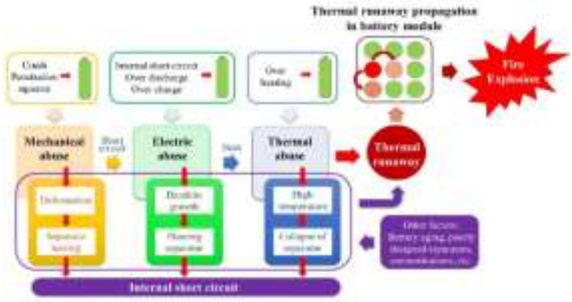

Figure 2.4 Lithium-Ion Batteries Fire incidents

2.22 Bian et .al [22] investigated how battery temperatures exceeding the recommended range caused capacity degradation and safety concerns. Current cooling techniques increased costs, size, and complexity. Low thermal conductivity limited the applications of phase change materials. Passive thermal management systems were found to be necessary to reduce maximum battery temperatures. HP/PCM systems reduced maximum temperatures by over 10%, while Paraffine-EG achieved better temperature uniformity. Higher driving speeds increased battery temperature faster. Simulation results showed a maximum error below 5%, and discharge depths showed a minimum error below 10% as shown in (figure 2.5).

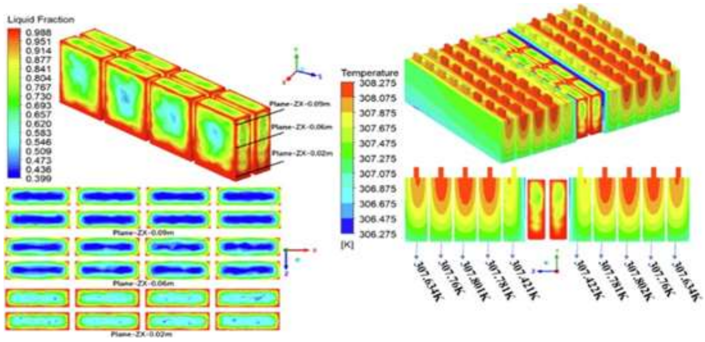

Figure 2.5 Liquid fraction and cell module temperature clouds under a single RT-31 heat sink

2.23 Zheng et al. [23] discussed the significant issues of environmental pollution and energy shortage, noting that lithium battery performance is influenced by working temperature. The optimal temperature range for lithium batteries was found to be 25-40°C, with excessive temperatures leading to a decline in performance. The maximum battery temperature could reach 54°C at a 2°C discharge rate, and temperature differences between batteries could reach 7°C. Inlet temperature was shown to significantly affect battery module temperature rise, and increasing inlet wind speed reduced both maximum and minimum temperatures. Experimental calculations verified the model's accuracy, with simulation results aligning closely with experimental data within 2.5°C as shown in (figure 2.6). The best temperature uniformity was achieved with 3mm fin spacing, and the maximum temperature difference between batteries was 7°C at a 2°C discharge rate.

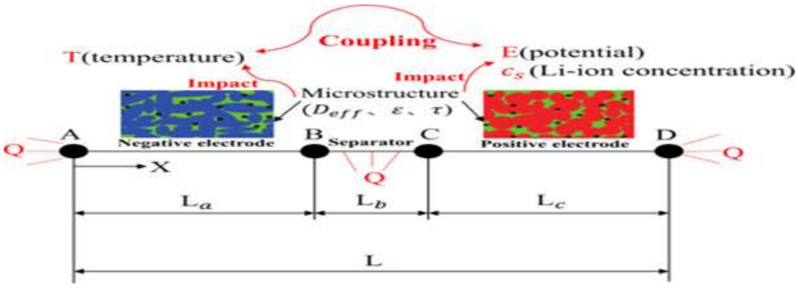

Figure 2.6 1D multi-scale electrochemical thermal coupling mode of LFP Battery

2.24 Fayaz et al. [24] investigated thermal performance issues in lithium-ion batteries (LIBs), including thermal runaway and fire hazards. The optimal operating temperature range for LIBs was found to be 25-40°C, with a maximum temperature difference of 5°C. High temperatures were shown to degrade battery efficiency and safety, while low temperatures reduced performance and lifespan. Cooling methods, as shown in (figure 2.7) such as shape-stabilized PCM and fin addition, were found to minimize the maximum temperature in battery modules. Experimental calculations and multi-objective optimization techniques were used to analyze design parameters and validate results. Genetic algorithms and loop heat pipe designs were found to reduce charging time and weight, while NSGA-II and TOPSIS provided optimal solutions for battery parameters.

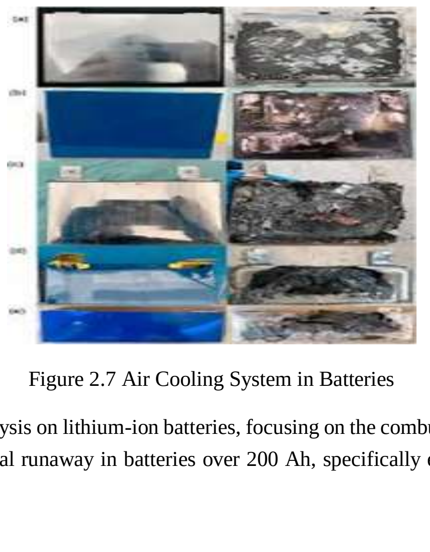

Figure 2.7 Air Cooling System in Batteries

2.25 Wei et al. [25] conducted an experimental analysis on lithium-ion batteries, focusing on the combustion and explosion risks during thermal runaway. The study addressed the limited research on thermal runaway in batteries over 200 Ah, specifically examining the characteristics of a 256 Ah battery.

The maximum temperature at the ejection zone reached 701.8°C ± 42°C, while the temperature at the safety valve outlet peaked at 679.2°C. The internal battery temperature exceeded the aluminum melting point of 660°C. The ejection temperature was found to significantly influence thermal hazard assessments. Gas generation was calculated under stable environmental conditions, and the mass loss rate was determined using specific equations. The ejection velocity of smoke was measured at 140 m/s, and the ejection velocity of flame was estimated at 55 m/s. The maximum temperature at the safety valve reached 701.8°C, and the pressure increase rate was normalized using the explosion index. The total ejection duration was 36.2 ± 4.7 seconds, with significant smoke emitted during thermal runaway as shown in (figure 2.8), and the pressure inside the chamber rapidly increased during ejection.

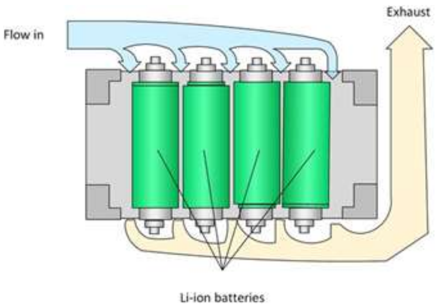

Figure 2.8 Comparative study on the thermal runway characteristic of Li (NixCoyMnz) O2 batteries

2.26 Tedjani et al. [26] addressed thermal management challenges in lithium-ion batteries for electric vehicles, particularly focusing on the risks associated with high discharge rates, which can lead to overheating and safety concerns. The study emphasized the need for improved energy density and thermal control solutions. It was found that the temperature during charging was higher than during discharging as shown in (figure 2.9), with the maximum temperature observed in the radial case reaching 46.91°C and the minimum temperature at 30°C as shown in (figure 2.10). The center temperature in the radial case reached 45°C. Experimental results were compared with FEA (Finite Element Analysis) results, with axial heat dissipation outperforming radial heat dissipation in experiments. Temperature readings were plotted against time intervals for analysis, and it was concluded that axial dissipation showed better performance, particularly during charging, where the temperature rise was higher than during discharging.

Figure 2.9 Temperature measurement in li-ion battery

Figure 2.10 Radial heat Dissipation

2.27 Dorsz et al. [27] examined fire hazards in electric vehicles, focusing on safety risks in enclosed structures. The study highlighted the need for improved fire safety systems and compared fire characteristics between electric vehicles (EVs) and internal combustion engine vehicles (ICEVs). It was found that lithium-ion batteries perform best between 20 and 30°C, but high temperatures can lead to battery overheating and fire. EV fires showed higher temperatures after 10-15 minutes, while ICEV fires reached higher maximum temperatures. Visibility decreased faster during ICEV fires after three minutes, and temperature significantly impacted evacuation conditions in enclosed spaces. The study utilized the CFD Fire Dynamic Simulator to calculate fire characteristics and simulate safety in enclosed structures during fires. EV fires exhibited different visibility and temperature profiles than ICEV fires, and the research concluded that further studies were necessary to improve fire safety in electric vehicles.

2.28 Liu et al. [28] explored the need for improved heat transfer performance in 3D-OHPs for high-power devices due to increasing heat dissipation issues. They compared the start-up temperatures and times of 3D-OHPs and analyzed temperature uniformity for hydrophilic 3D-OHPs. The filling ratio of 3D-OHPs was set at 50%, and heating power varied from 20 W to 80 W. Pressure sensor readings were used for vacuum verification, and temperature was measured using K-type thermocouples at multiple points. Uncertainty analysis was conducted to ensure accuracy. The results showed that the 3D-OHP demonstrated improved thermal performance and stability, with a temperature uniformity of 4.2°C and thermal conductivity of 3.7 W/m·K.

2.29 Zhang, J. et al. [29] examined the gas generation rates in lithium-ion batteries, revealing that these rates increased significantly, by approximately 25-50%, at lower states of charge (SOCs) (e.g., below 20% SOC). They documented the occurrence of multiple-peak features during violent thermal runaway (TR), with peak gas generation rates reaching as high as 15 liters per minute under certain conditions. The explosion limits of gas mixtures were found to shift, with variations noted between different cathode materials, indicating that some materials may lead to a more hazardous environment, with explosion limits changing by as much as 20% based on composition. Additionally, the study reported non-monotonic responses in explosion limits across SOCs, with notable reductions in explosivity observed when minor gas components (like CO_2 and H_2) were present, which could decrease the explosivity of mixtures by about 30-40%. The study underscored the critical influence of SOC and material choice on the safety and stability of lithium-ion batteries.

2.30 Lystianingrum et al. [30] investigated the risks associated with battery thermal runaway gas explosions, specifically analyzing the transport rules and gas composition through numerical modeling. They identified a range of gases produced during thermal runaway, including hydrogen (H2), carbon monoxide (CO), methane (CH4), acetylene (C2H2), and carbon dioxide (CO2), with average gas concentrations reaching 16.4% at the time of an explosion. The research utilized the STAMP (System-Theoretic Accident Model and Processes) model to explore the underlying causes of battery system accidents, revealing that gas movement facilitated by infrastructure, such as cable trenches, could significantly contribute to explosion risks. Notably, the study found that in certain areas, explosion overpressures exceeded 70 kPa, highlighting the serious dangers posed by indoor obstructions that could affect flame growth and explosive pressure. The findings emphasized the complexity of interconnected environments in enhancing explosion risks and contributed to a broader understanding of socio-technical systems, advocating for improved safety measures to mitigate such hazards.

2.31 Shen, X. et al. [31] utilized computational fluid dynamics (CFD) modeling to investigate battery thermal runaway incidents, focusing on a notable lithium-ion battery explosion in China. The research revealed that underground cable trenches could significantly facilitate the transport of thermal runaway gases to adjacent buildings, increasing the risk of explosions. It identified a variety of gases produced during thermal runaway, including hydrogen (H2), carbon monoxide (CO), methane (CH4), acetylene (C2H2), and carbon dioxide (CO2), with the average gas concentration reaching 16.4% at the time of the explosion. Additionally, the study noted that the configuration of surrounding obstacles could lead to explosion overpressure exceeding 70 kPa in certain areas, affecting flame growth and propagation. While several windows could aid in explosive venting, they also expanded the potential for flame damage. These findings highlighted the hazards posed by interconnected environments and emphasized the need for safety limits to prevent future battery-related accidents.

2.32 Zalosh, R. et al. [32] investigated battery thermal runaway incidents through computational fluid dynamics (CFD) modeling, focusing on a serious lithium-ion battery explosion that occurred in China. The study revealed that underground cable trenches facilitated the transport of thermal runaway gases, significantly increasing the risk to nearby buildings. An average gas concentration of 16.4% was identified at the time of the explosion, with hydrogen (H2), carbon monoxide (CO), methane (CH4), acetylene (C2H2), and carbon dioxide (CO2) present in the gas composition. The results indicated that explosion overpressure could exceed 70 kPa due to the configuration of surrounding obstacles, which also influenced flame propagation. Although windows could aid in explosive venting, they simultaneously widened the potential for fire damage. The findings underscored the hazards posed by interconnected environments and highlighted the necessity of establishing safety limits to prevent future battery-related accidents.

2.33 Cai, L. et al. [33] investigated firefighting solutions for battery energy storage systems, focusing on the challenges associated with battery cell fire suppression. The authors conducted a comprehensive literature review that highlighted various approaches and uncertainties in existing fire suppression strategies. Experimental results revealed the efficacy of water mist (WM) in cooling battery fires, with findings showing that WM increased the critical onset temperature for thermal runaway (TR) by 36°C. Moreover, the prolonged release of water mist was shown to effectively suppress TR propagation, underscoring its potential as a viable and efficient firefighting method for enhancing safety in energy storage applications. The study ultimately emphasized the importance of developing robust fire suppression techniques to mitigate risks associated with battery-related incidents.

2.34 Qiu, M. et al. [34] addressed the safety concerns associated with lithium-ion batteries, particularly their susceptibility to fire and thermal runaway (TR), which generates hazardous gases like hydrocarbons, hydrogen fluoride (HF), and carbon monoxide (CO). The study emphasized that aging batteries produced more gas and had diminished thermal stability, increasing the risk of incidents. The authors suggested that fire separation techniques could effectively delay the onset and spread of TR within battery modules. They highlighted the potential of phase-change materials for enhancing fire separation and thermal management in battery systems. However, they also noted a significant gap in research concerning TR gas formation from aged batteries, stressing the need for further investigation. Ultimately, the paper called for future studies to focus on developing safer lithium salts and binders to improve battery safety, while reinforcing that effective fire separation measures could mitigate the likelihood of fires or explosions.

2.35 Adhikari, N. et al. [35] studied the thermal behavior of Li-ion batteries, focusing on how cylindrical battery packs dissipate heat. Thermal evaluation was conducted using finite element analysis, investigating the mechanisms of internal heat generation. The research highlighted the importance of heat control for battery longevity. The study examined the temperature characteristics of Li-ion batteries, finding that radial heat dissipation was less efficient than axial heat dissipation. Improved thermal control was shown to extend the life and performance of batteries. Cooling was aided by thermal plates and coaxial tubes, and the research contributed to the development of better thermal management systems.

2.36 Peng et al. [36] investigated the performance and failure mechanisms of lithium-ion batteries under shock wave impacts, focusing on their safety in extreme conditions. The study found that shock wave compression led to a decrease in internal resistance and capacity, while increasing the battery's voltage, particularly as the State of Charge (SOC) decreased. Higher overpressure values resulted in increased voltage and decreased internal resistance, with a safety valve damage threshold identified at 0.92 MPa. Larger batteries, such as those with a 50Ah capacity, exhibited higher damage thresholds compared to smaller 37Ah batteries. The extent of rupture disk cracking, linked to capacity reduction, was more severe in oblique impacts compared to horizontal hits. Additionally, SOC played a role in how voltage varied under shock wave overpressure, affecting the battery's overall response to dynamic loads. The findings underscored the need for enhanced safety mechanisms to prevent catastrophic failures, particularly under high overpressure and oblique shock wave conditions.

2.37 Xiong et al. [37] focused on battery temperature management systems and proposed a design using flat heat pipes for effective heat dissipation. The study analyzed four biomimetic fin structural factors to optimize temperature regulation. It found that the maximum temperature was greatly influenced by the height of the protrusions on the fins, with taller protrusions improving temperature control. The research aimed to enhance the efficiency and safety of lithium-ion batteries by identifying ideal parameters for temperature management, crucial for maintaining optimal battery performance and preventing overheating. Specific numerical values were not provided, but the height of protrusions was highlighted as a key factor in regulating battery temperature.

2.38 Sauer, N. et al. [38] investigated the explosion risks associated with thermal runaway gases in lithium-ion batteries, particularly in home energy storage systems. Experiments were conducted in a typical North American garage environment, comparing impulse data and pressure rise with existing explosion models. The Mulpuru model was used to assess the risks. It was found that lithium iron phosphate (LFP) gas generated more pressure and impulse than nickel cobalt aluminum (NCA) gas. Small amounts of synthetic thermal runaway exhaust gas (synTREG) presented significant explosion risks. Specifically, although the overpressures inside the garage compartment peaked below the threshold for eardrum rupture, the garage door acted as a deflagration vent to release the pressure. The study emphasized the significant explosion risks posed by thermal runaway in home energy storage systems, particularly due to the pressure buildup from thermal runaway gases.

2.39 Urtnasan et al. [39] examined the effects of shock waves on lithium-ion batteries, focusing on how dynamic loading conditions influenced battery behavior and failure mechanisms. The research found that shock wave overpressure decreased internal resistance and increased voltage. The damage criteria for safety valves differed between 37Ah and 50Ah batteries, with 50Ah batteries having higher damage thresholds. Oblique strikes caused more severe damage than horizontal impacts, and the extent of rupture disk cracking correlated with capacity reduction. The study also identified that compression and thinning of isolators could lead to short circuits. Additionally, the state of charge (SOC) affected battery performance during impacts, influencing both the appearance and electrical properties of the battery under shock wave overpressure.

3. Conclusion

The provided studies collectively emphasize the critical need for effective thermal management in lithium-ion batteries (LIBs), especially for electric vehicles (EVs), to mitigate risks of overheating, thermal runaway (TR), and associated fire or explosion hazards. Key findings highlight several approaches and technologies aimed at maintaining battery temperatures within optimal ranges (generally 25-40°C) for safe and efficient operation. Various cooling systems are evaluated, including liquid cooling, heat pipes, phase change materials (PCMs), and hybrid methods like heat pipes combined with PCMs, which are proven to improve temperature uniformity and cooling efficiency. Innovative configurations, such as U-shaped channels, flat heat pipes (FHPs), and oscillating heat pipes (OHPs), enhance cooling by optimizing heat dissipation and reducing pressure drops.

Furthermore, the impact of environmental and operational extremes, such as high discharge rates and extreme temperatures, on battery safety and performance is addressed. Studies reveal that as state of charge (SoC) and temperatures increase, so does the likelihood of TR and hazardous gas emissions, which underscores the importance of fire separation and standardized control mechanisms. Advanced optimization techniques, including genetic algorithms and neural networks, are explored to refine design parameters for thermal efficiency.

The research concludes that integrating advanced cooling solutions, customized thermal management, and consistent monitoring is essential for enhancing LIB longevity, efficiency, and safety in high-demand applications like EVs.

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