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A COMPREHENSIVE REVIEW ON TECHIQUES FOR THERMAL MANAGEMENT OF LITHIUM-ION BATTERY

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ABSTRACT
As electric vehicles (EVs) become increasingly important in addressing environmental concerns and reducing dependence on fossil fuels the performance and safety of their power sources lithium-ion batteries are gaining major attention. One of the key challenges in battery operation is effective thermal management. Efficient thermal management of lithium-ion batteries (LIBs) is crucial to ensure performance, safety, and longevity in electric vehicles (EVs) and energy storage systems. Recent advances have focused on the integration of thermoelectric devices, liquid cooling, air-based systems, and phase change materials (PCMs) to maintain uniform temperature distribution and prevent overheating. Studies have demonstrated that thermoelectric coolers (TECs) and thermoelectric generators (TEGs) can effectively regulate battery temperature through solid-state heat transfer with compact structure and high controllability [4],[6], [8], [12], [18]. Experimental investigations reveal that TEC-assisted systems significantly improve heat dissipation and temperature uniformity in lithium-ion modules [5], [13], [19]. Additionally, hybrid cooling strategies combining TECs with PCMs, liquid cooling, or air flow have been proposed to enhance efficiency under high load or fast charging conditions [7], [19], [25],[28]. Complementary approaches using heat pipes, air channels, and liquid metal also demonstrate strong potential for advanced EV battery applications [9], [29],[32]. This paper reviews and synthesizes recent developments in thermoelectric and hybrid cooling systems for lithium-ion battery thermal management, highlighting the performance improvements, challenges, and future research directions in this rapidly evolving field.

Keywords: Electric vehicles (EVs) Lithium-ion batteries Battery Thermal Management system (BTMS) Phase change materials (PCM's), Heat pipes, Air cooling Liquid cooling, Thermoelectric cooling.

I. Introduction

II. Electric vehicles (EVs) widely use lithium-ion batteries as their primary energy storage system due to their high energy density, lightweight construction, and long-life time The vehicle converting chemical energy into electrical energy through the movement of lithium ions between the cathode and anode during charging and discharging cycles. This technology enables (EVs) to achieve longer driving ranges, faster acceleration, and efficient energy use making it central to the advancement and adoption of clean, green transportation. The batteries are made up of multiple cells assembled into modules and packs, designed for safety, durability, and optimal performance. The lithium-ion batteries are recyclable to support environmental sustainability in the shift to electric mobility an effective thermal management system is vital for maintaining the safety, efficiency, and longevity of lithium-ion batteries, especially in high-demand applications such as electric vehicles. The research highlights the importance of controlling heat generation during charge discharge cycles to prevent thermal runaway, capacity loss, and safety hazards. To address these challenges a range of thermal management techniques have been developed including passive systems like phase change materials (PCM) and heat pipes, and active systems such as air and liquid cooling solutions. Hybrid systems combining multiple approaches have also gained prominence aiming to optimize temperature uniformity and energy efficiency[2]. Recent advancements emphasize the design of novel heat transfer structures, including microchannel and oscillating heat pipes, which have demonstrated excellent cooling performance in confined spaces. Simultaneously, innovative materials with enhanced thermal conductivity, along with improved heat transfer mechanisms like water spray cooling, are being researched to further enhance thermal regulation. Despite significant progress, challenges remain in developing scalable, energy-efficient, and cost-effective solutions that operate reliably under extreme conditions, such as rapid charging and low ambient temperatures. The ongoing research underscores the critical role of interdisciplinary collaboration to bring forward next-generation thermal management strategies suitable for broad applications from consumer electronics to large-scale energy storage systems. The expanding use of lithium-ion batteries, noted for high energy density and long cycle life, but sensitive to temperature fluctuations that impact performance and safety. Cooling methods including air, liquid, phase change material (PCM)[3], and heat pipe systems are reviewed with their pros and cons. TEC-based BTMS offer precise thermal control, important for mitigating internal temperature variations and maintaining batteries within an optimal temperature range (298–313 K).The Seebeck and Peltier effects, underpins both thermoelectric generators and coolers. TEC modules consist of paired N-type and P-type semiconductors arranged between ceramic plates, enabling directional heat transfer and both cooling and heating modes by adjusting current flow and magnitude. Flexible TECs, designed on bendable substrates, extend applications to wearable devices and flexible batteries. The critical role battery thermal management systems (BTMS) play in ensuring the safety, stability, and longevity of batteries used in fields like electric vehicles and mobile devices. Traditional cooling techniques—such as air and liquid cooling—have been widely studied and implemented due to their simplicity and scalability [20], [22],[26]. However, they often face challenges such as uneven temperature distribution, slow transient response, and increased system complexity. To overcome these limitations, researchers have investigated solid-state thermoelectric devices, which can act as both coolers and generators, offering compact size, rapid response, and precise temperature control [4], [8], [12]. For instance, Alsaqoor [4] and Li et al. [5], [13] experimentally analysed thermoelectric coolers (TECs) integrated with battery modules and demonstrated significant temperature reduction under various heat transfer conditions.

Hybrid approaches have also emerged as promising solutions. Systems combining TECs with phase change materials (PCMs) or liquid cooling channels have shown enhanced heat dissipation and improved thermal uniformity [7], [18], [19], [27]. Studies by Liu et al. [18] and Mahamud and Park [20] revealed that reciprocating air flow and fin-based structures can further optimize cooling efficiency. Moreover, recent developments in liquid metal cooling [9] and heat pipe–based designs [29],[32] have expanded the range of viable options for next-generation EV battery packs.

Overall, thermoelectric and hybrid cooling technologies represent an innovative direction for the future of lithium-ion battery thermal management. Continued research is needed to improve energy efficiency, reduce cost, and enhance integration with fast-charging and high-energy-density battery systems [11], [28].

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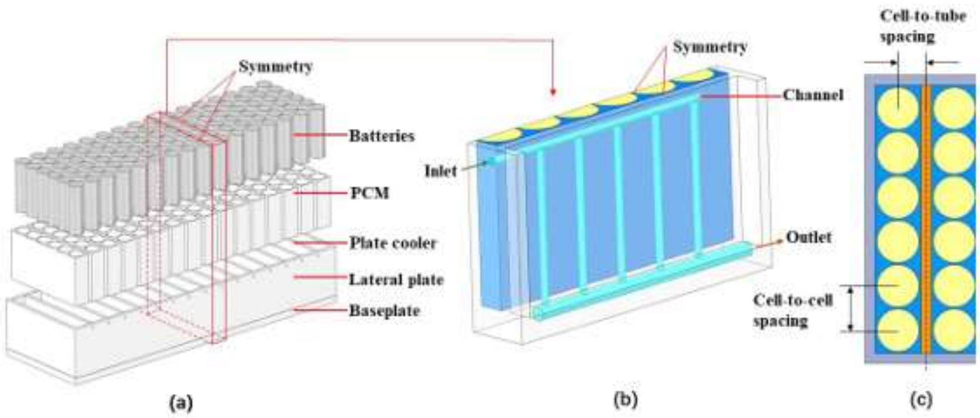
III. **Literature**

IV. **Thermal management of lithium-ion batteries by using phase changing material**

V. Effective Battery Thermal Management Systems (BTMS) are crucial for maintaining lithium-ion battery performance, safety, and longevity under high-rate charge–discharge conditions [1] Passive thermal strategies such as phase change materials (PCMs) efficiently absorb excess heat using latent heat of fusion, maintaining near-isothermal conditions during discharge [2] . However, PCMs suffer from low thermal conductivity and potential leakage, which limits their standalone performance in high-power applications [3] .

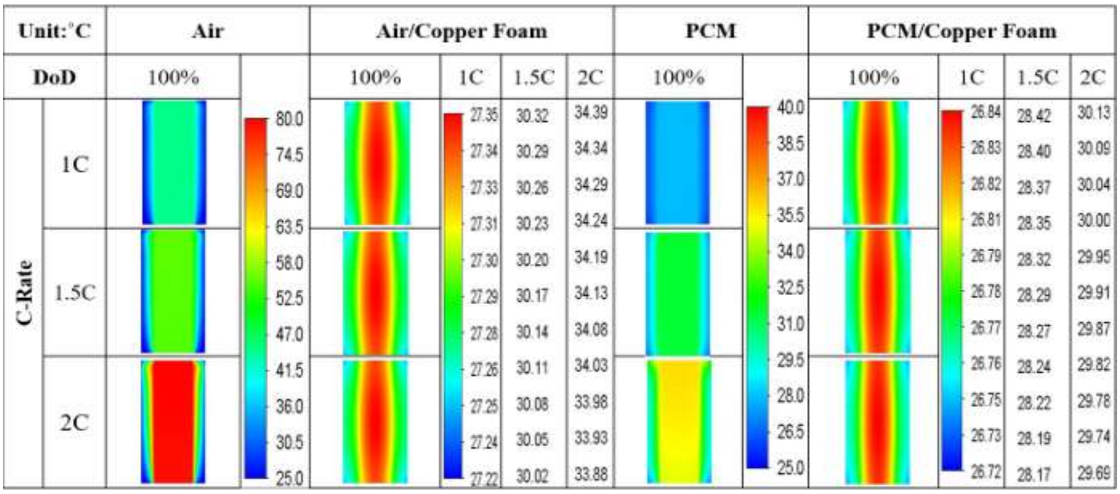
VI. To overcome this, hybrid PCM–liquid cooling systems have emerged as a promising solution that combines the energy absorption of PCM with the high convective efficiency of active cooling [1] . Figure 1 illustrates the hybrid BTMS module structure, showing how a PCM layer surrounds cylindrical cells while a cold plate beneath circulates coolant through microchannels. This configuration achieved a temperature uniformity below 5 °C and a maximum temperature reduction of over 20 °C compared to pure air cooling, validating the synergy between PCM and liquid cooling [1] .



VII.

VIII. Figure 1. Schematic of PCM + liquid-cooling hybrid BTMS module (*Processes 2023, 11, 57*, Fig. 1) [1]

IX. Another major enhancement involves embedding metal foams into the PCM matrix to improve heat conduction and reduce temperature gradients [2] . *Energies 2024 (17, 1553)* investigated copper-foam-based PCM modules and demonstrated that the foam's porous structure creates high-conductivity pathways between cells. As shown in Figure 2, the foam-enhanced PCM system reduced maximum cell temperature from about 80 °C to 30 °C compared with conventional air cooling, while maintaining temperature uniformity across all cells [2] .

X. 

XI. Figure 2. Comparison of temperature distribution using air, PCM, and copper-foam + PCM cooling (*Energies 2024, 17, 1553,* Fig. 6) [2]

XII. The porosity of the metal foam plays a crucial role in balancing conduction and PCM capacity. *Energies 2024* further reported that an optimal porosity of 0.95 yields the best thermal performance, since too low porosity limits PCM volume while too high reduces thermal pathways [2] . This combination of PCM latent heat and copper-foam conduction ensures faster temperature equalization and lower hot-spot formation, especially at 3C discharge rates [2] .

XIII. Material optimization also contributes to improved PCM efficiency. *Materials 2020 (13, 4622)* analyzed expanded graphite (EG) and fin structures for PCM enhancement and found that EG composites increased thermal conductivity up to 60 times while maintaining effective latent-heat storage [3] . Figure 3 from that paper illustrates various fin geometries—rectangular, circular, and longitudinal—and highlights that rectangular fins provided superior temperature uniformity and heat dissipation due to larger contact area and directional conduction [3] .

XIV. 

XV. Figure 3. Common fin geometries used in PCM-based BTMS (*Materials 2020, 13, 4622,* Fig. 13) [3]

XVI. Collectively, these studies show that combining PCM's latent-heat buffering with the enhanced conduction of copper foams or fins—and integrating active cooling for thermal recovery—produces the most reliable BTMS for electric vehicles and high-power energy-storage systems [1–3] . Hybrid PCM-liquid-cooling systems with optimized foam porosity and fin geometry consistently maintain lower and more uniform temperatures across multiple cycles, demonstrating strong potential for large-format battery modules and next-generation electric-mobility applications [1–3].

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2.1 Thermal management of lithium-ion batteries by using Thermoelectric cooling

Thermoelectric cooling system

Thermoelectric coolers (TECs) have emerged as a promising technology for thermal management in various applications, including lithium-ion batteries used in electric vehicles (EVs). TECs offer distinct advantages such as precise temperature control, compactness, and the ability to operate without moving parts or refrigerants. These features make them highly reliable and environmentally friendly compared to traditional cooling systems. Additionally, TECs can rapidly respond to temperature changes, enabling efficient heat dissipation and improved battery safety by preventing overheating and thermal runaway. Their solid-state nature also allows for silent operation and easy integration into battery packs, which is crucial for optimizing performance, extending battery life, and enhancing overall vehicle efficiency. The advantages of thermoelectric cooling thus position TECs as a key component in the advancement of next-generation battery thermal management systems.[7]

Thermoelectric cooling (TEC) systems integrated with forced convection (FC) represent an advanced approach to thermal management in lithium-ion batteries, particularly for electric vehicles. TECs provide precise, solid-state cooling without moving parts or refrigerants, ensuring high reliability and environmental friendliness. When combined with forced convection using fans or liquid pumps to actively move air or coolant . TEC systems achieve significantly improved heat dissipation by enhancing the transfer of heat away from the battery surface. This synergistic integration enables faster temperature reduction, better temperature uniformity across battery cells, and prevention of thermal hotspots, which are crucial for battery safety, performance, and longevity. The use of forced convection amplifies the thermoelectric cooling efficiency, allowing lithium-ion batteries to operate within optimal temperature ranges even under high load or extreme ambient conditions. This hybrid cooling approach is gaining attention as a compact, scalable, and energy-efficient solution for next-generation battery thermal management in electric vehicles[5].

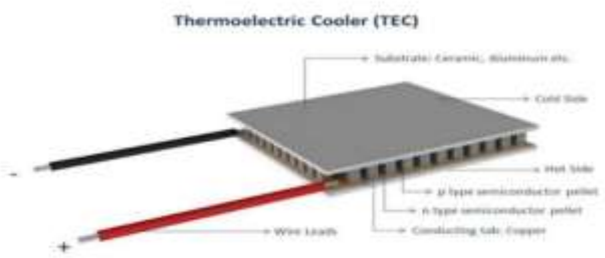

Fig-1: Thermoelectric cooler [12]

Forced convection is a type of heat transfer mechanism where fluid motion is generated by an external source such as a pump, fan, or suction device. This forced movement of fluid increases the rate of heat transfer between a solid surface and the fluid compared to natural convection, where fluid motion arises slowly from buoyancy forces due to temperature differences. Various battery thermal management systems (BTMS) have been widely installed on HEVs and EVs [7]. During the repeated charging and discharging process, the battery module would generate a large amount of heat, especially at a relatively high rate. The BTMS can avoid the rapid increase in temperature when the battery module is maintained at high temperature during a long time in some remote regions. Increasing the corresponding auxiliary equipment to maintain the battery module at proper temperature is the best solution for HEVs and EVs, utilized the refrigeration system to cool a lead acid-based. The flow field and temperature distribution of two- and six-layer configurations containing 24 batteries were analysed in detail by experiments and numerical simulations. The results showed that the passive air cooling system utilizing natural convection (N-C) can maintain battery temperature at optimal values between 20° C and 30° C. Situ et al. [8] designed a coupled battery thermal management (BTM) system based on a novel quaternary phase change material plate for balancing the temperature in rectangular LiFePO4 battery modules; meanwhile, the paraffin, expanded graphite, low-density polyethylene, and copper mesh were combined into a quaternary PCMP to strengthen the heat transfer. The results revealed that the double out stretched copper mesh through the phase change material plate could disturb the air flow tempestuously and give rise to a decrease in thermal resistance; thus, the temperature distribution inside the battery and temperature uniformity within the battery module were both better optimized. However, the battery module cannot be applied during the operating status because the batteries have to continue working at a hot environment.

The demand for efficient and reliable battery systems has grown significantly across various industries, including automotive, renewable energy, and consumer electronics. One critical aspect of battery performance that often receives less attention is temperature management. Maintaining optimal operating temperatures is essential for maximizing battery efficiency, extending lifespan, and ensuring safety. Traditional methods of battery cooling typically rely on bulky and energy-intensive systems, which can be challenging to integrate into compact or portable applications. However, advancements in thermoelectric technology offer promising solutions to this challenge. Thermoelectric devices, such as Thermoelectric Generators (TEGs) and Thermoelectric Coolers (TECs), utilize the thermoelectric effect to control temperature without the need for moving parts or harmful refrigerants [11]. The stability, reliability, and simplification of the system need to be improved for fixed investment and power consumption. Long-term safety preservation of battery temperature is also important. In recent years, the thermoelectric effect in a semiconductor has been widely investigated because it can produce temperature gradient when an electric current is launched. And thermoelectric generator (TEG) cooling can promptly create a relatively lower temperature than the surrounding temperature, which could not need extra moving parts for converting electrical capacity into refrigerating capacity. The degree of cooling can easily be adjusted depending on the current size. The refrigeration effect can also be maintained for a long time without extra maintenance. This characteristic not only can improve the system reliability but also can simplify the system structure for thermal management. Therefore, thermoelectric generator (TEG) cooling is an effective approach for thermal management of a battery module [6]. To overcome the negative effects of heat dissipation, considerable efforts have been invested to investigate an effective cooling system for a battery module, according to the heat transfer medium, which should include the air-based thermal management systems such as natural or air-forced cooling [8,9], liquid-based thermal management systems such as heat pipe or fluid liquid cooling [30, 31], and phase change material-based thermal management system. However, air-based thermal management systems would hinder the heat dissipation among the batteries due to their relatively low thermal conductivity and heat transferring efficiency. Meanwhile, the liquid-based thermal management systems with complex structures have to increase the extra cost, which also easily causes short circuit if leakage of the liquid occurs in the system and leads to serious thermal runaway problem for the battery module. In addition, a phase change material-based thermal management system has to affect the weight of battery module increment and its cost is extremely high [10]. The instant performance of heat dissipation is also challenging. In this study, a new thermal management model of a temperature control battery based on semiconductor refrigeration is proposed. This model is characterized by the real-time feedback of the temperature of the battery module through the rapid cooling/heating of the semiconductor and the effect of the fan. The temperature control module is reflected in the temperature control heat management model by the temperature control module of the battery protection board. The design and specific operation of the experiment are as follows. First, adiabatic cotton is used to wrap the experiment box to create an adiabatic environment. Then, the parameters of the temperature control module are fully tested. Finally, the discharge experiments of the battery module at different rates and conditions are tested [6].

Working principle of Thermoelectric cooler (TEC)

The fundamental concepts behind the operation of the thermoelectric effect are the Seebeck effect and the Peltier effect. A phenomenon that results from a thermal gradient between two materials or semiconductors, the Seebeck effect was originally noticed in 1821. This disparity results in a variation in voltage between the two compounds. The Peltier effect, which was initially observed in 1834, pertains to the outcome of an electric current traversing dissimilar material's. This causes an exothermic reaction to take place at the interface of the materials, as well as the generation of irreversible Joule heat. The assessment of the TEG materials is conducted using the merit figure of ZT. This figure is determined by three fundamental physical qualities, namely, the electrical conductivity, Seebeck coefficient, and thermal conductivity, which are associated with the features of N-type and P-type materials [13].

A typical TEC consists of numerous P-type and N-type semiconductor junctions that are electrically coupled in series via metallic interconnects, usually made of copper. These junctions are thermally connected in parallel, creating a single-stage cooler [41]. When a DC power supply of lower voltage is connected to a TEC, thermal energy is transferred from one end of the cooler to the opposite end. Consequently, one side of the TEC gets cooled while the other side is heated. Fig. 1 illustrates a TEC module that functions as a thermoelectric refrigerator. The passage of electrical current occurs from the N-type element to the P-type element inside this module. The cold junction's temperature (TC) lowers as transmission of heat occurs from the surroundings to the cold junction at a reduced temperature. When electrons in a transport system travel across a cold junction, they change energy levels, going from a lower one in the P-type component to a higher one in the N-type component.

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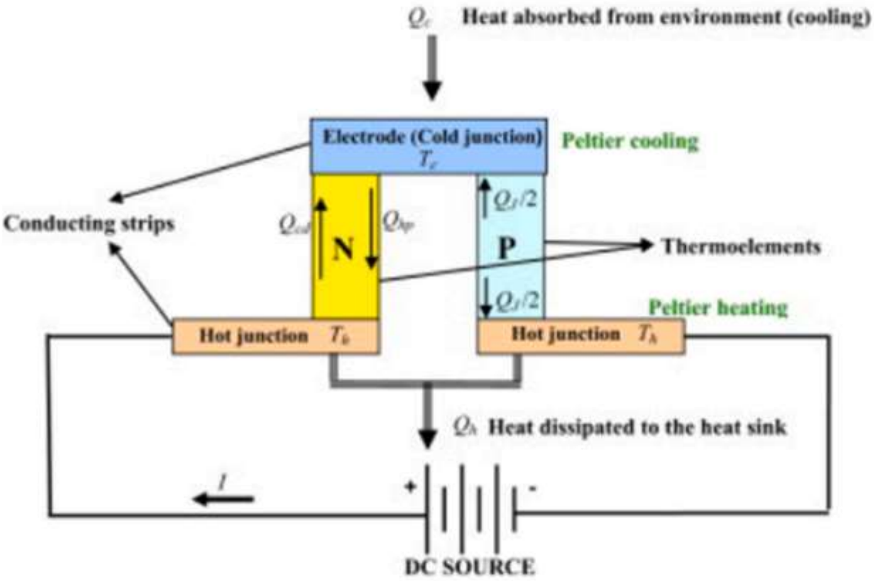

Fig-2: Diagram illustrating the working of a TEC [6]

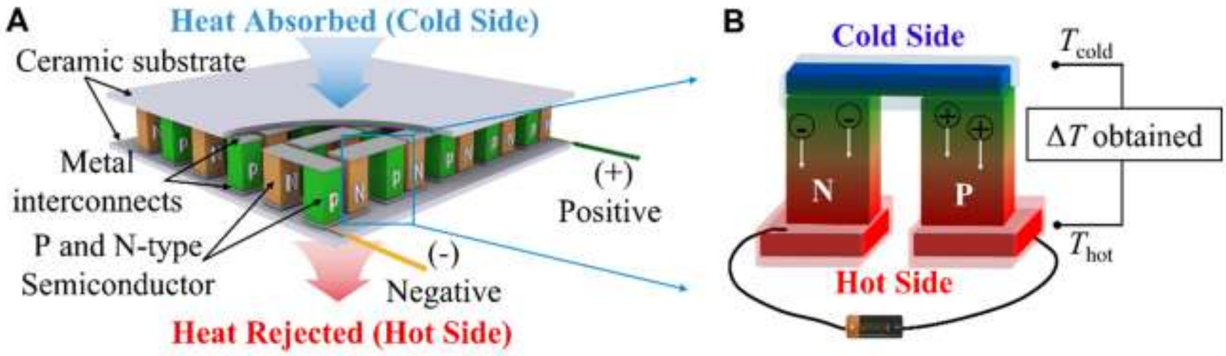

Fig-3: Thermoelectric device and principle: (A) Schematic diagram showcasing the components of the thermoelectric device; (B) The principle behind TEC, relies on a single pair comprising N-type and P-type thermoelectric materials. TEC: Thermoelectric cooler.[11]

TECs are primarily used for temperature regulation in various laboratory instruments and testing equipment. Applications include cold compress devices, portable insulin cases, mobile medicine cabinets, and polymerase chain reaction (PCR) testing equipment [8]. In the aerospace and defence sectors, TECs are utilized for temperature management in detectors and sensors, cooling of laser systems, regulating temperatures in flight suits, and cooling equipment housings [11]. Within the industrial sector, they offer precise temperature control in products such as display chillers, smoke gas cooling systems, charge-coupled device (CCD) image sensors, laser diodes, and dew point meter [11]. In the automotive sector, TEC is primarily used for onboard refrigerators, temperature-controlled cup holders, heated and cooled seats, as well as thermal management in human-machine interface devices, power batteries, sensors, and other equipment. With further technological advancements, TEC technology may achieve higher efficiency and more precise cooling effects, meeting the demand for high-performance cooling technology across various fields.

Working of Peltier effect

The Peltier effect is a phenomenon that is taken into consideration in TEC systems, while the Seebeck effect is a phenomenon that is regarded in TEG systems. The TEC has been widely used in residential cooling and solar energy system batteries. Many research studies have extensively used the thermal energy control TEC system integrated inside the BTMS of EVs. The condition indicated above is achieved by supplying the appropriate electrical energy to both ends of the TEC to establish a temperature gradient between its cold and hot surfaces. In contrast, the valuation of the electrical energy contribution and the produced materials within the context of TEC is contingent upon the magnitude of the temperature differential. The continuous provision of energy to the TEC is unattainable owing to the escalating impact of joules. The Joule heating effect refers to the heat created by the passage of electric current in a metallic conductor. This phenomenon entails the application of heat to the cathode filament of an X-ray tube, increasing the temperature of its previously cool surface. Hence, attaining optimal operational efficiency for TEC necessitates using a suitable control mechanism [3]. Integrating TEC and TEG into a single model has emerged as a promising technological advancement in refrigeration applications and BTMS. TEGs, which operate based on the Seebeck effect, have many advantages. One such benefit is the ability of TEGs to collect waste heat from the hot surface of TECs and convert it into electrical energy [46]. This generated energy is feedback energy for TECs, optimizing their performance. Additionally, TEGs contribute to the overall lowering of temperature in the battery pack of EVs, enhancing their efficiency and functionality [6].

TEC Method in FC

Lithium-ion batteries stand out in the field of electrochemical energy storage due to their high energy density, long cycle life, low self-discharge rate, and absence of memory effect, among other characteristics, securing an important position [15]. In recent years, their application has continued to expand, covering various fields such as portable electronic devices, electric vehicles, home energy storage, and industrial energy storage, permeating widely across all levels of society [16]. This imposes higher requirements on the safety and energy density of lithium-ion batteries. However, lithium-ion batteries are extremely sensitive to temperature conditions, with their performance, lifespan, and safety significantly affected by temperature. The ideal operating temperature range for lithium-ion batteries should be maintained between 298 and 313 K, with temperature variations within the battery module precisely controlled to within 5 K [11]. In high-temperature environments, the decomposition of the solid electrolyte interface (SEI) film may accelerate, potentially leading to thermal runaway incidents. In low-temperature environments, the viscosity of the electrolyte increases, thereby affecting the charge-discharge performance of the battery and potentially accelerating lithium deposition reactions, leading to the formation of lithium plating or dendrites. In addition, excessive temperature gradients within the module can lead to differences in discharge performance between individual cells, thereby affecting the overall discharge performance of the module. Therefore, to effectively control battery temperature and improve temperature uniformity within the module, implementing efficient forced convection systems is crucial. Currently, FC can be categorized based on the heat transfer medium used, including air cooling systems, liquid cooling systems, phase change material (PCM) cooling systems, and heat pipe cooling systems. Each cooling technique has its advantages and disadvantages [Table 1]. FC based on TECs demonstrate significant advantages because they are relatively quiet and stable.

Table-1: Advantages and Disadvantages of cooling methods in FC .

Cooling method	Advantages	Disadvantages
Air cooling	1. Simple structure, low cost 2. Lightweight 3. Ease of maintenance	1. Insufficient cooling capacity 2. low thermal conductivity 3. Poor control of battery 4. Temperature uniformity
Liquid cooling	1. High specific heat capacity 2. High thermal efficiency 3. Better cooling effect 4. Achieve uniform temperature distribution	1. Complex structure 2. Heavyweight 3. High cost 4. Risk of liquid leakage 5. Difficult in maintenance
PCM	1. Small size 2. Low cost 3. High thermal density 4. High energy storage density 5. Good stability	1. Risk of PCM leakage 2. Heat not dispersing 3. Combustible
Heat pipes	1. High thermal conductivity 2. Efficient heat dissipation 3. Fast heating speed 4. Good uniformity 5. Safety and reliability	1. Complex structure 2. High manufacturing cost 3. Difficult in maintenance 4. Low capacity and low efficiency
TEC	1. No moving parts 2. Small and lightweight 3. Maintenance free 4. Acoustically silent and electrically “quiet” 5. Heating and cooling with the same module 6. Wide operating temperature range 7. High precise temperature control (to within 0.1 °C	1. Low thermal efficiency 2. Additional power requirement

Currently, the application of TECs in FC is still in an exploratory phase, with significant room for improving the cooling performance of battery packs. Addressing this challenge remains pressing, as existing solutions have not yet fully optimized performance or resolved critical issues. This review aims to explore innovative TEC-based FC approaches and provide a comprehensive evaluation on the advantages and limitations. By examining recent developments and specific details related to heat generation in lithium-ion batteries, the review identifies gaps in current knowledge and highlights areas where TECs can be more effectively utilized. The unique contribution of this study lies in its detailed analysis of various TEC-based FC methods, synthesizing their benefits and drawbacks. This comprehensive overview offers valuable insights and guidance for advancing research in this field, making it a timely and essential review for both current and future developments in battery thermal management.

Designing an effective BTMS requires a thorough understanding of the heat generation and transfer mechanisms in power batteries. During charging and discharging, the heat produced in a power battery primarily consists of four components: polarization heat, reaction heat, side reaction heat, and Joule heat[17] . For lithium-ion power batteries, the side reaction heat is mainly caused by battery aging, which generates very little heat due to the slow aging process and can therefore be neglected. When considering battery heat generation, only reaction heat, polarization heat, and Joule heat need to be considered. Reaction heat (Qr) is the heat generated by complex chemical reactions inside the battery; meanwhile, the presence of internal resistance in the battery also produces Joule heat (Qj); polarization heat (Qp) is generated by the polarization resistance per unit time[17] . In the power system of new energy vehicles, batteries need to have characteristics such as large capacity and high C-rate. Moreover, the high temperatures generated by the battery pack, especially under uncertain environmental conditions, increase operational risks, potentially leading to fires or even explosions. Therefore, researching the heat generation mechanism of lithium-ion batteries over varying periods is crucial to ensure their safe use. Understanding the heat transfer characteristics of lithium-ion batteries is essential for more accurate thermal simulation and modelling [21]. Heat transfer occurs through three main methods: conduction, convection, and radiation. Considering the structure of lithium-ion batteries and their pack configuration, it is known that heat transfer primarily occurs through conduction within the battery and convection externally.

Structure of TEC-based FC

The schematic diagram illustrates a simplified FC using TEC modules in Figure 2. The TEC module can be divided into three parts: the cold side, the hot side, and the p-n junction [Figure 2A] [18] . The top (cold side) of the TEC is connected to the battery, while the bottom (hot side) is connected to the air or a liquid as a heat transfer medium via a heat sink. The heat produced by the battery is transferred from the top to the bottom, causing the top to cool down and thus reducing the battery temperature. Precise temperature control is achieved by adjusting the current. Additionally, the system can heat the battery by reversing the direction of the TEC's current. Therefore, with the TEC layout fixed, the battery temperature can be controlled to the desired level by changing the direction and magnitude of the DC .The heat generation and heat conduction processes at the cold and hot sides of the TEC can be expressed as:

$$Q_c = SI_{TEC}T_c - 0.5I_{TEC}^2R_{TEC} - \kappa_{TEC}(T_h - T_c)$$

$$Q_h = SI_{TEC}T_h + 0.5I_{TEC}^2R_{TEC} - \kappa_{TEC}(T_h - T_c)$$

where Qc and Qh represent the heat absorbed at the cold side and the heat generated at the hot side, respectively; Tc and Th denote the average temperatures at the cold and hot sides of the TEC, with a temperature difference ΔT between the cold and hot sides; S, R, and κ represent the Seebeck coefficient, electrical resistance, and thermal conductivity of the TEC module, respectively. The input power to the TEC is denoted as P and is defined as:

$$P = Q_h - Q_c = I_{TEC}^2 \ R_{TEC} + SI_{TEC}(T_h - T_c)$$

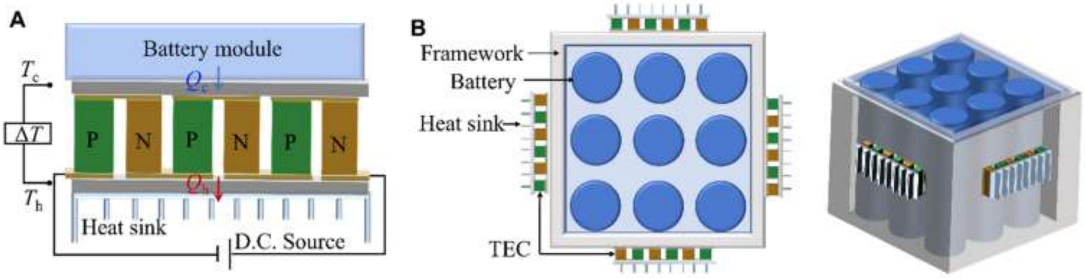

Fig-4: Heat transfer mechanisms of TEC-based FC : (A) The architecture of the TEC-based BTMS, features a schematic diagram illustrating heat transfer within the FC utilizing TEC; (B) BTMS model based on TEC, presented from both a top view and a front view. TEC: Thermoelectric cooler; FC: battery thermal management system. [11]

The coefficient of performance (COP) represents the cooling efficiency of a thermoelectric refrigeration system, and it can be expressed as:

$$COP_{max} = \frac{Q_c}{P}$$

A steady-state simplified energy balance model is commonly used to calculate the thermal performance of a TEC [19] . This model is based on a core assumption that the Joule heat generated within the module is evenly distributed between the cold side and the hot side, with each end receiving 50% of the Joule heat. However, during the transfer of heat between different components, thermal resistance inevitably leads to the generation of temperature differences. Therefore, when conducting relevant theoretical studies, it is also important to fully consider the influence of various thermal resistance factors[11].

FC based on TEC and air cooling

Air cooling provides benefits such as simple structure, high reliability, and low cost. However, its effectiveness deteriorates at elevated ambient temperatures (313~328 K), and it cannot maintain uniform temperature distribution among battery cells[19]. Alaoui proposed a TEC-FC system that incorporates forced air cooling . This system is illustrated in Figure 5A; in a single unit of a 48-cell BTMS, six TEC modules [selected the 9506/031/400 TEC module, each module has a 55 mm (L) × 55 mm (W) × 4.85 mm (H) single-stage, 31-couple, 40-amp module with a plain ceramic surface] were installed on the surface of 60 Ah lithium-ion pouch cells and bolted onto an aluminium plate.

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Additionally, to enhance heat dissipation, four fans were installed on the right side of the heat sink to exhaust the heat generated by the battery effectively. Evaluation results showed that under a constant discharge current of 3C, the highest heat rate observed was 168 W, and each TEC module managed up to 28 W. The system used 919 Wh to lower the battery pack temperature from 330.6 to 319.8 K; under US06 cycle conditions, the system consumed 317 Wh to lower the battery pack temperature by 8.82 K. Meanwhile, the COP of the system was approximately 0.9 for regular testing and approximately 1.2 for cycle testing, indicating good performance in maintaining battery temperature and reducing energy consumption. In 2017, Alaoui designed a TECFC system combined with forced air cooling, with four TEC modules (9506/031/400 TEC module, TEC maximum cooling power is 92 W) installed on the positive and negative poles as well as the centre of the battery pack, applied to lithium-ion batteries recovered from electric vehicles [Figure 5B] [11] .

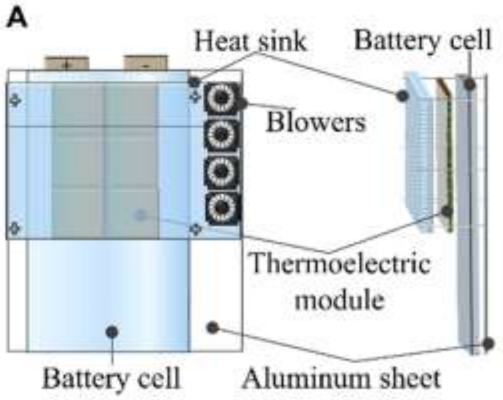

Fig-5A: TEC-based BTMS combined with air cooling: (A) Schematic diagrams of BTMS integrating TEC and forced air cooling[11]

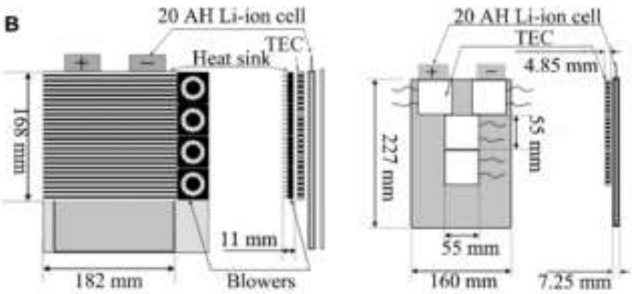

Fig-5B: Physical assembly includes Li-ion battery cells, TEC modules, heatsink, and blowers. Reprinted with permission Copyright 2017, Elsevier [11]

Experiments were conducted using refurbished 20 Ah lithium iron phosphate ($LiFePO_4$) battery cells, measuring their surface temperature distribution, which showed that the highest temperatures were observed near the positive and negative poles, with the central region exhibiting comparatively lower temperatures. The experimental results indicated that under normal conditions, the BTMS, as a passive thermal management system, could maintain battery cooling without additional energy consumption. However, under extreme conditions, all TEC modules needed to be activated, accounting for 43.81% of the total energy of the battery pack. Ultimately, the proposed BTMS was compared to a forced air cooling system. Under extreme conditions, while the forced air system exhibited lower energy

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consumption, it resulted in higher battery surface temperatures. This accelerated battery aging and approached the safety temperature limit [20].

Li et al. designed a BTMS integrating TEC with forced-convection (F-C) technology to achieve temperature control for nine cylindrical lithium-ion battery modules [Figure 5C] [8] . When the TEC module (TEC1- 12706, L × W × H is 40 mm × 40 mm × 3.8 mm, the working voltage is 12 V and working current is 6 A) was energized with DC, the cold-side temperature of the TEG rapidly decreased from 301.82 to 282.56 K in less than five minutes, and then the temperature change inside the TEG slowed down, with the cold-side reaching a limit temperature of 277.71 K. In contrast, the hot-side temperature rapidly increased from 302.01 to 314.03 K, with a limit temperature of 314.22 K. This phenomenon occurred due to two main reasons. Firstly, the current flowed through both the P-type and N-type semiconductors, generating a temperature difference based on the Seebeck effect.

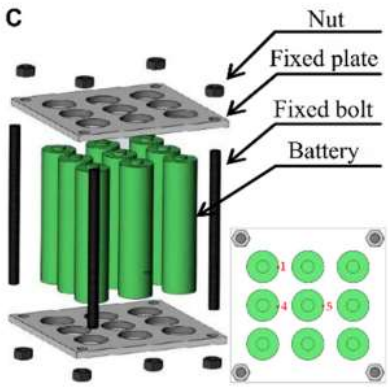


Fig-5C: 3D diagram illustrating the battery module and temperature measurement points; temperature-time diagram of the cold and hot sides of TEC[8] .Copyright 2019, Hindaw.

The generated heat is conducted through the ceramic material, elevating the temperature on both sides of the TEG until a new equilibrium was established. By conducting comparative experiments with a natural cooling system without TEC (N-C cooling model) and a forced cooling system without TEC (F-C cooling model), the study results showed that under a 5D discharge rate, the battery module combined with TEC and F-C cooling technology had a maximum temperature of only 338.43 K, which was lower than the 343.52 K observed in the F-C cooling model and the 351.30 K in the N-C cooling model. The energy consumption analysis shows that the pure TEG exhibits the highest energy waste at 26.64 J. The FC-313 K + TEG-313 K (TEG coupled with FC, both at 313 K) consumes 15.95 J, while the FC + TEG-313 K (FC coupled with TEG at 313 K) is the most energy efficient, using only 12.38 J, making it the optimal choice for TEG temperature control[14].

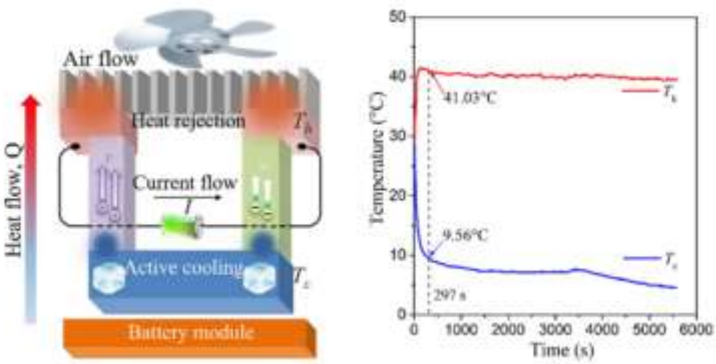


Fig 5D: TEC: Thermoelectric cooler; BTMS: battery thermal management system[11].

Cooling method	Temperature drop	Conclusion
TEC + Forced Air	8.8 – 10.8 °C	Effective battery pack cooling
TEC + FC (Air)	13 °C vs. FC-only; 24 °C at cold side	Best energy efficiency (12.38 J)
TEC	≈ 20–25 °C below ambient	Controlled by input current

Table-2:

As per the Table-2 thermoelectric cooling systems, especially when combined with forced convection, can reduce battery surface temperature by roughly 9–13 °C and TEC module cold sides by up to 25 °C, maintaining batteries within their optimal range (298–313 K) for safety and longevity.

2.3 4 Thermal management of lithium-ion battery using Air cooling

Amith A. Kulkarni et al [44] presented the new technology, which in turn increases the area of application for the technology. Among that, one of them is the agricultural application, such as the adding artificial intelligence (AI) and Internet of things (IoT) in the machinery is to make it a smart device that will be capable of making decision-making capacity based on the past experiences and learning, it is the system that includes IoT (Internet of things), where automated machine learning of the plethora of devices that make up the system is the primary focus. This technology is used for the application of agricultural systems, and it solves a number of issues that are prevalent in the agricultural industry. These issues include crop disease infestations, inadequate storage management, inadequate pesticide control, inadequate weed management, and inadequate irrigation and drainage facilities. Additionally, this technology makes use of wireless networks for the monitoring and controlling of its operations.

C. L. de Abreu et al [45] presented a comprehensive literature study here with the purpose of investigating the utilization of Artificial Intelligence (AI) and the Internet of Things (IoT) in agricultural settings. To understand the current applications, challenges, but also future benefits of AI and IoT in agriculture as well as the potential to reduce resource wastage but also assist in feeding the world's growing population, a total of 50 articles were located and analysed in accordance with the PRISMA methodology. This was done in order to gain a better understanding of these topics. On the basis of the presented information, it is anticipated that this study will function as a reference to enhance the reader's existing understanding of AI and IoT in the agricultural business.

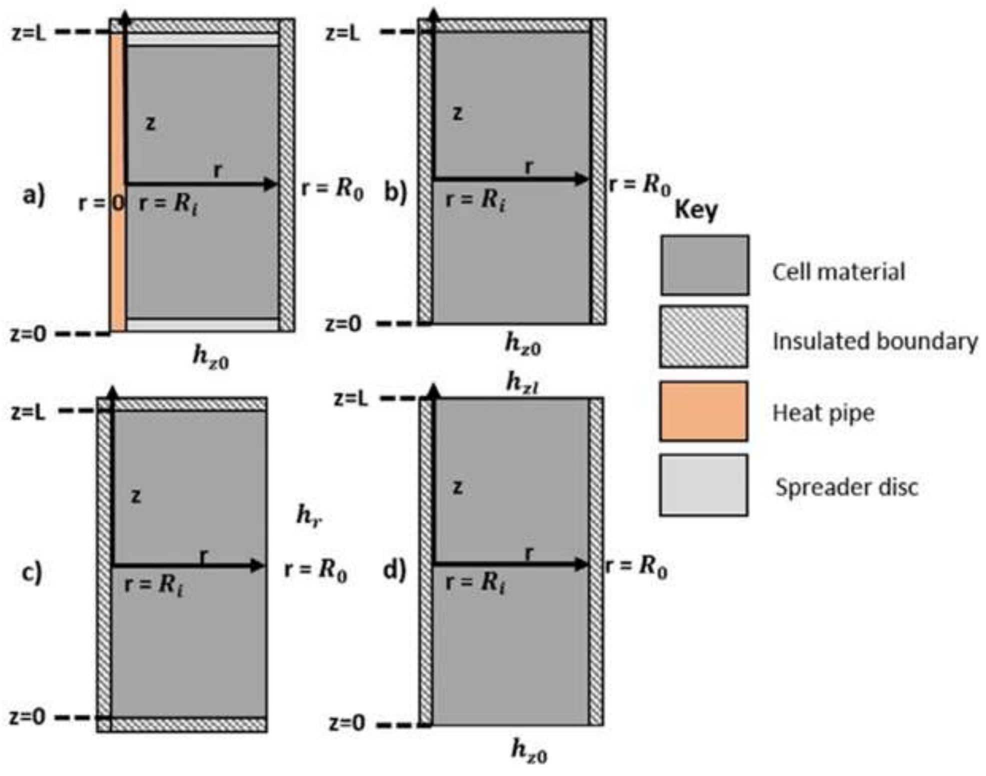
MohdJavaid et al [46] investigated the use of AI in agriculture and its implications. This article provides a quick overview of the process of using AI in agriculture as well as some of the agricultural metrics that AI monitors. In conclusion, the authors highlighted and spoke about some of the most notable uses of AI in agriculture.

Nermeen Gamal Rezk et al [47] developed an intelligent strategy that is based on the combination of a wrapper feature selection approach and a PART classification methodology. For the purpose of forecasting agricultural production and drought conditions. There are five different datasets that are used in the estimation process for the proposed technique. In light of the findings, it was determined that the proposed approach is robust, accurate, and exact in its classification and prediction of agricultural production and drought when compared to the methods that are already in use. According to the findings, the suggested technique was the one that provided the most accurate drought prediction, as well as the productivity of crops including Bajra, Soybean, Jowar, and Sugarcane.

Jitendra Singh et al [48] created a prediction method for crop selection with a total of 28 attributes, based on the qualities of the soil (including its physical properties, chemical properties, and biological properties). In order to provide enough training data for machine learning algorithms, five distinct copies of a hypothetical dataset were produced. This system adheres to the phases of the analytics maturity curve, which are descriptive, predictive, and prescriptive respectively. The system consists of two distinct components. First, it determines the kind of crop that will be most beneficial to the health of the soil. The next step is for the system to provide recommendations on how the health of the chosen soil sample may be improved, with the goal of increasing the crop's potential for financial gain. This study focuses on decision trees, naive Bayes models, and random forest algorithms. It contributes to improved crop selection decisions by improving prediction accuracy.

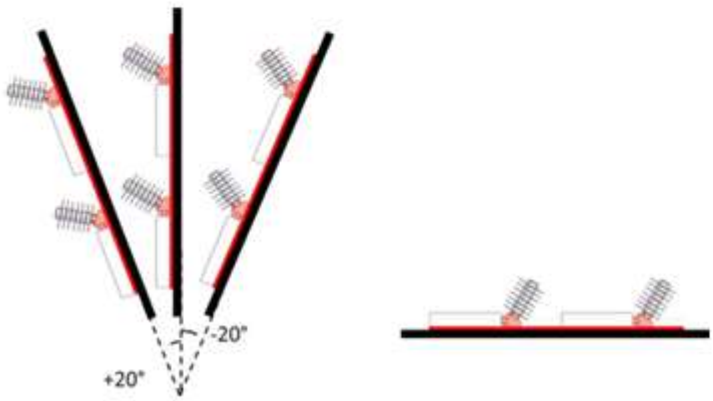
2.4 Heat pipes are increasingly studied for battery thermal management systems (BTMS) in electric and hybrid vehicles due to their high thermal conductivity, robustness, and passive operation. Weragoda et al. (2023) provide a comprehensive review highlighting mechanisms of Li-ion battery heat generation, heat pipe operation, and recent developments in various heat pipe types—tubular, flat, oscillating, loop, and mini/micro heat pipes—applied to BTMS. Their review notes that while heat pipes maintain optimum cell temperatures effectively, understanding limitations under rapid heat fluctuations and complex heat loads is critical for commercialization. Tubular heat pipes with enhanced surface contact using fins and phase change materials (PCM) have been experimentally shown to keep battery temperatures below 50°C and maintain thermal uniformity within 5°C. Internal cooling using heat pipes integrated into cell cores has also yielded improvements in thermal resistance reduction.[29]

[Fig. 1. Cell cooling arrangement with heat pipe spreader disc]



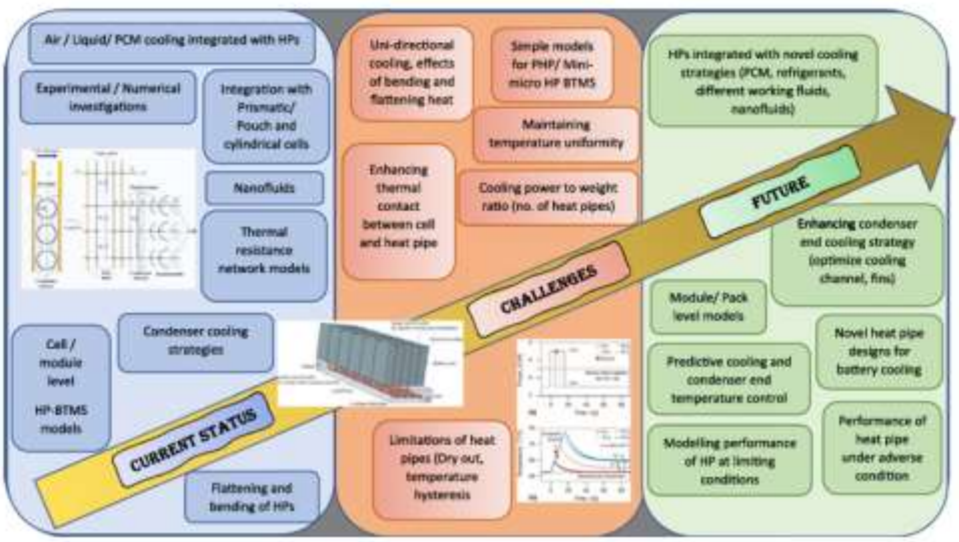
Rao et al. (2013) experimentally evaluated heat pipe cooling for electric vehicle batteries, demonstrating effective control of maximum battery temperature below 50°C for heat generation rates under 50 W. Their heat pipe system distributed four copper tube heat pipes evenly along the battery surface, with experimental data confirming temperature rise and non-uniformity remain within acceptable limits under steady and transient conditions. Inclination tests mimicking varying road grades showed that vertical and slightly inclined heat pipes maintain good heat transfer, while horizontal positions decreased thermal efficiency. Complementary forced ventilation designs using chimney and fan-assisted airflow were explored to augment condenser heat dissipation, with fan-assisted designs providing better performance at low power consumption.[30]

[Fig. 2. Heat pipe cooling system experimental configurations]



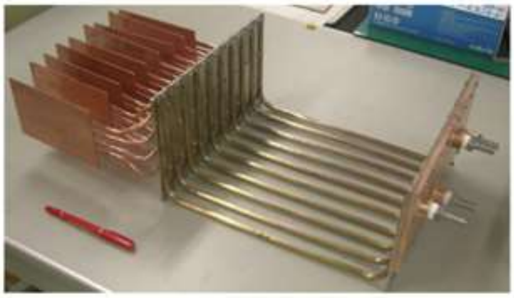
Smith et al. (2018) designed a heat pipe-based BTMS incorporating heat pipe cooling plates and remote heat transfer heat pipes coupled with liquid-cooled cold plates for prismatic lithium-ion battery modules. Their system effectively dissipated heat loads up to 400 W per module while maintaining cell temperatures below 55°C and inter-cell temperature uniformity within 5°C. Thermal resistance network analysis revealed that the remote heat pipe module accounted for the largest share of thermal resistance, highlighting design trade-offs associated with heat pipe length and condenser dimensions. Their test setup demonstrated stable temperature profiles across heat pipe cooling plates, remote heat pipes, and cold plates, showing the system's capability for stable operation under high heat dissipation demands.[31]

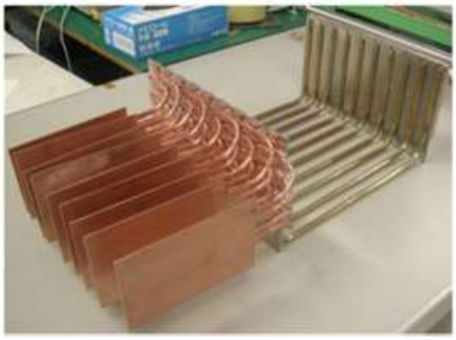
[Fig. 3. Complete heat pipe thermal management system layout]



Tran et al. (2014) investigated heat pipe cooling for HEV lithium-ion batteries through experiments emulating driving conditions and inclinations. They confirmed heat pipe modules coupled with low ventilation rates maintained battery cell temperatures below their optimal limit of 50°C, outperforming natural convection alone. Chimney-assisted ventilation moderately improved heat dissipation but was insufficient alone for high heat loads, whereas fan-driven airflows significantly enhanced condenser cooling. Transient testing simulating realistic HEV power cycles indicated cell temperature fluctuations remained within safe bounds, supporting heat pipe BTMS viability for dynamic operation. [32]

[Fig. 4. Battery temperature versus heat load under heat pipe cooling]





2.4 Conclusion

This comprehensive review demonstrates that effective thermal management is absolutely essential for maintaining the safety, reliability, performance, and lifespan of lithium-ion batteries—especially in high-demand sectors such as electric vehicles and large-scale energy storage. Passive strategies like phase change materials (PCM) and heat pipes deliver valuable heat absorption and transfer benefits but face constraints around thermal conductivity, leakage, and scalability. Active approaches, including air and liquid cooling systems, provide better temperature uniformity and dissipation but can involve increased design complexity, higher energy consumption, and potential risks such as coolant leakage. Hybrid systems—such as the integration of PCM with liquid cooling or combining thermoelectric modules (TECs) with forced convection—offer a promising pathway to synergistically exploit the advantages of both passive and active methods, maintaining optimal battery temperatures even under rapid charging or extreme environmental conditions. The adoption of intelligent controls, AI-based algorithms, advanced materials, and waste-heat recovery solutions (like TEG–TEC hybrids) further enhance system adaptability and efficiency

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