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Advances in solid-state and flexible thermoelectric coolers for battery thermal management systems

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Abstract

Battery thermal management systems (BTMS) play a crucial role in various fields such as electric vehicles and mobile devices, as their performance directly affects the safety, stability, and lifespan of the equipment. Thermoelectric coolers (TECs), utilizing the thermoelectric effect for temperature regulation and cooling, offer unique advantages for BTMS. Compared to traditional cooling techniques, TEC-based BTMS provides precise temperature control, which allows customized adjustment of temperatures in different areas, meeting the strict thermal management demands in various fields. This offers more reliable and efficient thermal management solutions for applications in electric vehicles and mobile devices. Furthermore, flexible TECs can provide more efficient thermal management for flexible batteries. This article timely and extensively explores several solid-state and flexible TEC-based BTMS technologies, including combinations with air cooling, liquid cooling, phase-change cooling, heat pipe cooling, and various cooling composite techniques. Battery heat generation models and the analysis process of TEC-based BTMS are first discussed. An objective evaluation of the advantages and disadvantages of various TEC-based BTMS approaches is provided, along with discussions on reasonable solutions and future development trends, aiming to provide a reference for designing optimal BTMS. In the end, we point out that it is crucial to select appropriate cooling technologies according to user requirements and to combine multiple cooling technologies for meeting thermal management needs in different application scenarios.

Keywords: Thermoelectric cooler, battery thermal management system, air cooling, liquid cooling, phase change material, hybrid cooling

INTRODUCTION

Thermoelectric technology based on the thermoelectric effect enables direct conversion between heat and electricity. The discovery of the Seebeck effect in 1821, the Peltier effect in 1834, and the Thomson effect in 1855 together form a complete system of thermoelectric effects, providing the theoretical basis for the application of thermoelectric generators (TEG) and thermoelectric coolers (TEC)[1,2]. The Seebeck effect enables the generation of electricity from a temperature difference, while the Peltier effect enables thermoelectric cooling[3]. Thermoelectric modules are arranged in series electrically and in parallel thermally, consisting of N-type and P-type semiconductors inserted between ceramic plates [Figure 1A]. These ceramic plates maintain mechanical integrity and simultaneously act as electrical insulators for the cooling and heating surfaces, ensuring the stability and safety of the thermoelectric modules[4].

Figure 1B shows a schematic TEC, which is based on the Peltier effect. In such a TEC, P-type and N-type semiconductors are connected in series via metal plates. When a voltage is applied across the conductors, one side of the TEC exhibits a cooling effect, while the other side shows a heating phenomenon, thereby achieving directional heat transfer[5-7]. Semiconductor-based TEC operates on direct current (DC) and connects the cold side of the device to the object requiring cooling, while the hot side is connected to a heat sink[5-7]. By adjusting the voltage and current, precise control of cooling capacity and temperature can be achieved continuously. Within the same system and without altering the structural conditions, simply changing the direction of the current allows for the transition between cooling and heating modes. Therefore, TECs can serve as efficient temperature controllers[4]. In addition, flexible TECs are solid-state or flexible thermoelectric modules designed to operate on flexible substrates[7]. Their flexibility makes them suitable for various applications requiring flexible thermal management solutions, such as wearable devices, medical instruments, and electronic products. Flexible TECs typically consist of flexible substrates, thermoelectric materials, and electrodes. The design and manufacturing of these TECs need to consider the characteristics of flexible materials and the balance between cooling efficiency and cooling power.

TEC boasts high precision control and rapid response. Unlike conventional mechanical refrigeration, it does not require moving parts such as compressors or refrigerants, eliminating emissions and environmental pollution. It stands as an ideal solid-state, high-efficiency cooling and thermal management technology[8]. TEC, with its irreplaceable advantages and characteristics such as flexibility, diversity, and reliability, has become a key technology supporting numerous modern industries[9-15], and has provided significant economic value in areas such as semiconductor refrigeration and bidirectional precise temperature control[2]. It finds wide applications across various sectors including consumer electronics, telecommunications, medical experiments, aerospace defense, industrial processes, and automotive industries. In consumer electronics, its typical applications include precise temperature control in confined spaces or achieving cooling and heating effects, such as in constant-temperature wine cabinets, electronic refrigerators, hot and cold water dispensers, electronic air conditioners, beer dispensers, constant-temperature mattress pads, dehumidifiers, smartphone cooling clips, and water-ion hair dryers[16]. In the field of telecommunications, employing TEC for precise active temperature control of optical modules,

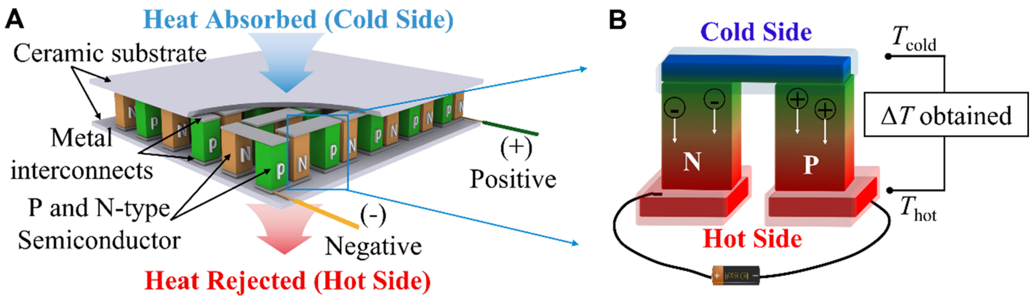

Figure 1. Thermoelectric device and principle: (A) Schematic diagram showcasing the components of the thermoelectric device; (B) The principle behind TEC, relies on a single pair comprising N-type and P-type thermoelectric materials. TEC: Thermoelectric cooler.

maintaining them in a stable temperature environment, stands as the primary technique ensuring the effective operation and extended lifespan of the optical modules[3]. In the medical field, 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[17,18]. In the aerospace and defense sectors, TECs are utilized for temperature management in detectors and sensors, cooling of laser systems, regulating temperatures in flight suits, and cooling equipment housings[19]. 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 meters[20]. 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[21,22]. 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.

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[23-25]. 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[26]. 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[27]. 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[28]. In high-temperature environments, the decomposition of the solid electrolyte interface (SEI) film may accelerate, potentially leading to thermal runaway incidents[29,30]. 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[29]. 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 battery thermal management systems (BTMS) is crucial. Currently, BTMS 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[31]. Each cooling technique has its advantages and disadvantages [Table 1]. BTMS based on TECs demonstrate significant advantages because they are relatively quiet and stable. By finely adjusting the

Table 1. Advantages and disadvantages of the cooling method in BTMS

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 pipe	(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) (8) Environmentally friendly (9) Flexibility	(1) Low thermal efficiency (2) Additional power requirement

BTMS: Battery thermal management system; PCM: phase change material; TEC: thermoelectric cooler.

voltage, they can achieve better cooling performance and precise temperature control. Relevant experiments and simulations have proven their feasibility and practicality in BTMS, providing strong support for the application of thermoelectric technology in battery thermal management[32,33]. Furthermore, compared to solid-state batteries, flexible lithium-ion batteries are specially designed batteries with flexible and bendable characteristics, allowing them to adapt to various shapes and curved surfaces[34,35]. They typically consist of a flexible substrate, lithium-ion conductive materials, electrolytes, and electrodes. This design enables flexible lithium-ion batteries to be easily integrated into various portable and wearable devices, such as smartwatches, smart glasses, and wearable medical devices. The features of flexible lithium-ion batteries include lightweight, thinness, and high customizability, making them have broad application prospects in modern electronic products. Therefore, flexible TEC is one of the excellent solutions designed for their BTMS.

Currently, the application of TECs in BTMS 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 BTMS 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 BTMS 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.

PRINCIPLES

Lithium battery heating principles and heat transfer characteristics

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[36]. 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 (Q_r) is the heat generated by complex chemical reactions inside the battery; meanwhile, the presence of internal resistance in the battery also produces Joule heat (Q_j); polarization heat (Q_p) is generated by the polarization resistance per unit time[36]. 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 modeling. 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. Therefore, current heat dissipation techniques mainly leverage these two heat transfer methods.

Structure of TEC-based BTMS

The schematic diagram illustrates a simplified BTMS 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][37,38]. 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:

$$Q_c = SI_{TEC}T_c - 0.5I_{TEC}^2R_{TEC} - \kappa_{TEC}(T_h - T_c) \tag{1}$$

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

where Q_c and Q_h represent the heat absorbed at the cold side and the heat generated at the hot side, respectively; T_c and T_h 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:

$$P = Q_h - Q_c = I_{TEC}^2 \ R_{TEC} + SI_{TEC}(T_h - T_c) \tag{3}$$

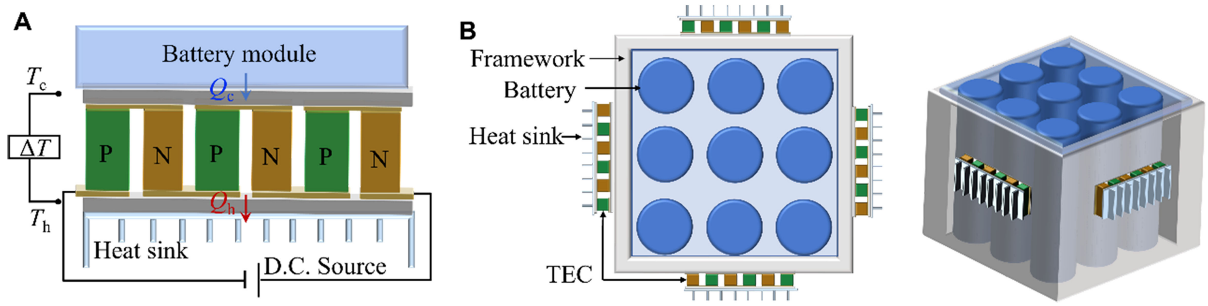

Figure 2. Architecture and heat transfer mechanisms of TEC-based BTMS: (A) The architecture of the TEC-based BTMS, features a schematic diagram illustrating heat transfer within the BTMS utilizing TEC; (B) BTMS model based on TEC, presented from both a top view and a front view. TEC: Thermoelectric cooler; BTMS: battery thermal management system.

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

$$COP_{\max} = \frac{Q_c}{P} \tag{4}$$

A steady-state simplified energy balance model is commonly used to calculate the thermal performance of a TEC[39]. 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[40][Buchalik, 2021 #3870].

Figure 2B illustrates the model of the TEC-based BTMS. To optimize the cooling effect, the coupling between the TEC and the battery module needs to be carefully designed. Research by Hunt *et al.* has shown that under rapid discharge (10 min), heat dissipation through the positive and negative terminal posts is more efficient than surface heat dissipation from the battery[41]. After 1,000 cycles, the reversible capacity loss of batteries with surface heat dissipation was three times higher compared to those with heat dissipation through the terminal posts. This is mainly attributed to the fact that batteries with surface heat dissipation experience greater internal temperature gradients, leading to uneven current distribution within the battery. On the other hand, heat dissipation through the terminal posts promotes a more uniform temperature distribution inside the battery, reducing uneven current distribution and improving the cycle life of lithium-ion batteries[41]. Song *et al.* offered a BTMS integrating semiconductor thermoelectric devices with PCMs and constructed a corresponding three-dimensional battery pack model[38]. Through numerical studies, the impact of semiconductor thermoelectric device layout on system performance was thoroughly investigated. The research findings suggest that placing the thermoelectric devices on both sides of the minimum dimension of the battery pack can significantly enhance temperature uniformity and effectively prolong the insulation process[38]. Furthermore, by adjusting the shape or arrangement of battery cells, the cooling performance and temperature uniformity can also be optimized. Wang *et al.* conducted a comprehensive study on how various battery cell arrangements - rectangular, hexagonal, and circular - affect the thermal performance of battery modules[42]. After considering cost factors comprehensively, it was found that the 5 × 5 cubic structures performed best in terms of cooling capacity. From the perspective of space utilization, a hexagonal arrangement of 19 battery cells exhibited the best cooling capability[42]. Fan *et al.* designed a battery pack comprising 32 high-energy-density cylindrical lithium-ion batteries arranged in various configurations, including orderly, staggered, and crossed arrangements[43]. Their findings revealed that the orderly arrangement provided the most effective cooling performance and temperature uniformity , followed by the staggered arrangement, with the crossed arrangement performing the least effectively[43].

Numerical method

When selecting numerical analysis methods, reducing research time is always a crucial consideration. Hence, researchers from different fields continue to explore more excellent methods to achieve more accurate research results in their respective areas. For the design and simulation work of BTMS based on TEC, choosing appropriate software can greatly enhance the efficiency and accuracy of design and simulation. Currently, commonly used design and simulation software include: (1) COMSOL Multiphysics: It is a multi-physics simulation software that can simulate complex physical phenomena including heat conduction, fluid flow, electromagnetic fields, *etc*. In BTMS design, it can accurately model the temperature distribution of battery packs, the cooling effect of TEC, and the overall thermal performance of the system[44-46]; (2) ANSYS Fluent: As a computational fluid dynamics simulation software, it plays an important role in simulating processes such as fluid flow, heat transfer, and chemical reactions. In BTMS, it can effectively simulate the airflow around battery packs and analyze the impact of convective heat transfer on battery temperature[47-49]; (3) Simulink: As an important module of MATLAB, it is mainly used for modeling and simulating dynamic systems. In BTMS, it can build battery thermal models, TEC control models, and dynamic response models of the entire system, facilitating system parameter optimization and performance analysis[46,50]. Different software has its characteristics and applicability, so the selection should consider design requirements, system complexity, and other factors comprehensively. Moreover, to ensure the accuracy of the results, it is usually necessary to validate and correct the simulation model with experimental data[44,50].

The thermal distribution analysis of the BTMS based on TEC involves the following steps[33,39,51]: (1) System Modeling and Setup: After determining the materials of system components, their physical properties, and heat transfer characteristics, use specialized thermal simulation software (such as COMSOL, ANSYS Fluent, *etc.*) to establish a three-dimensional model of the BTMS. This includes key components such as the battery pack, TEC, heat dissipation structures, *etc.*, [Figure 3]; (2) Initial and Boundary Conditions Setup: Set the initial conditions and boundary conditions of the model according to the actual working environment and operating conditions. For example, set the ambient temperature, convective heat transfer coefficient, TEC operating parameters, *etc*. In Figure 3, the red dots represent the temperature probe positions; (3) Grid Independence Analysis: Divide the model into grids for numerical computation. The refinement level of the grid affects the accuracy of the calculation results, so choose an appropriate grid size based on actual requirements; (4) Design and Validation: Set simulation parameters, and analyze the temperature distribution characteristics of the battery pack under various operating conditions, such as the highest temperature point, temperature gradient, *etc*. Evaluate the cooling effect of the TEC and analyze its role in improving battery thermal performance. Based on the analysis results, optimize the design of the BTMS, such as adjusting the layout of the TEC, changing the heat dissipation structure, *etc*. If necessary, validate the accuracy of the simulation results through experiments.

PROGRESS AND ADVANCES

Over the past decade, thermoelectrics have garnered significant attention due to their potential applications in eco-friendly energy solutions and energy management[2,6,52,53]. TEC has found application in the automotive industry, particularly playing a significant role in climate control systems for electric vehicles and cooling/heating systems for luxury car seats[22,54]. In 2003, Salameh and Alaoui first proposed the use of a thermoelectric module based on the Peltier effect for thermal management of passenger cabins and battery

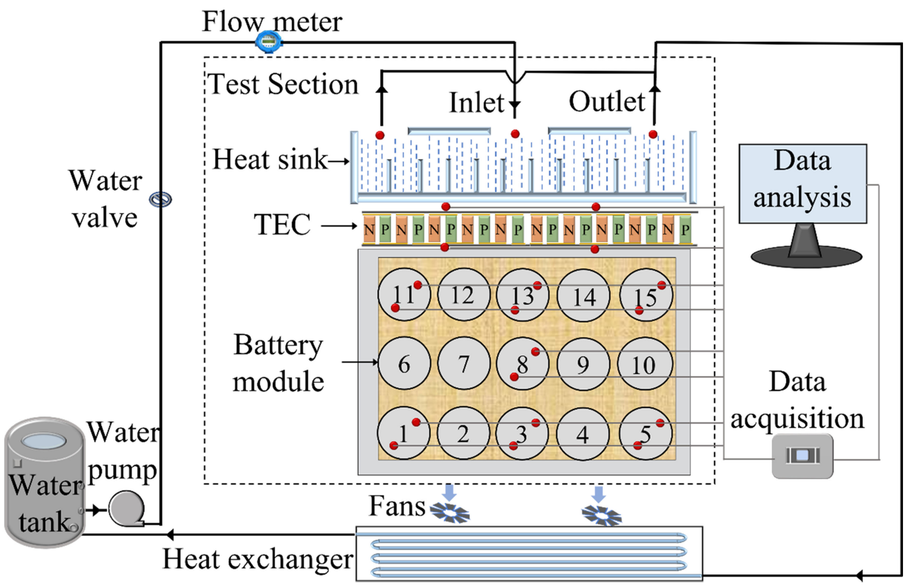

Figure 3. Schematic of the BTMS test setup based on TEC. BTMS: Battery thermal management system; TEC: thermoelectric cooler.

compartments in electric vehicles[55]. The basic unit of thermal management consists of 12 thermoelectric cells (a typical unit size is about 5-30 mm) sandwiched between two heat sinks [Figure 4A]. The hot side of the thermoelectric module must be connected to a heat sink, whose primary function is to effectively dissipate the heat and Joule heat generated during the module's operation. Similarly, the cold side is attached to another heat sink, which introduces cold air into the system to lower the temperature at the cold side and thereby reduce the ΔT, with a fan used as the cooling air supply device. Additionally, between the module and the heat sink, a "spacer block" is set up, the thickness of which precisely separates the hot side heat sink from the cold side heat sink, maximizing heat transfer. Its structure is depicted in Figure 4B: comprising three thermoelectric cells [Figure 4A]; a thermoelectric controller (providing power, controlling temperature by regulating current); a hose system (distributing processed air to different compartments); and a blower fan (forcing "cooling" or "heating" air into the electric vehicle). Three thermoelectric modules are applied to the front battery compartment, rear battery compartment, and cabin of the electric vehicle, and the temperature variation in the battery compartment during the thermoelectric module heating test is recorded [Figure 4C]. It was found that the temperature increased linearly in the first six minutes and then began to saturate, with the thermoelectric element reaching 310 K, while the internal temperature of the battery compartment was 302 K. The authors also recorded the temperature variation in the battery compartment during the cooling test [Figure 4D], finding that the temperature increased linearly in the first four minutes and then began to saturate. Eventually, the thermoelectric element reached 282.5 K, while the internal temperature of the battery compartment was 286 K. This study highlights the significant economic benefits of TECs in thermal management for electric and hybrid vehicles. Their advantages include a long lifespan, lightweight design, low maintenance costs, environmental friendliness (no freon required), and high cooling efficiency[55,56].

TEC, as part of BTMS, offers numerous advantages such as being relatively quiet, stable, and capable of achieving more precise temperature control by adjusting voltage[57]. However, there is a major drawback to using thermoelectric systems in BTMS, namely their low thermal efficiency, which requires additional energy to maintain operation, thus reducing the overall thermal efficiency of the battery pack itself[58,59]. Given this, most current research focuses on exploring hybrid applications of TEC with other cooling

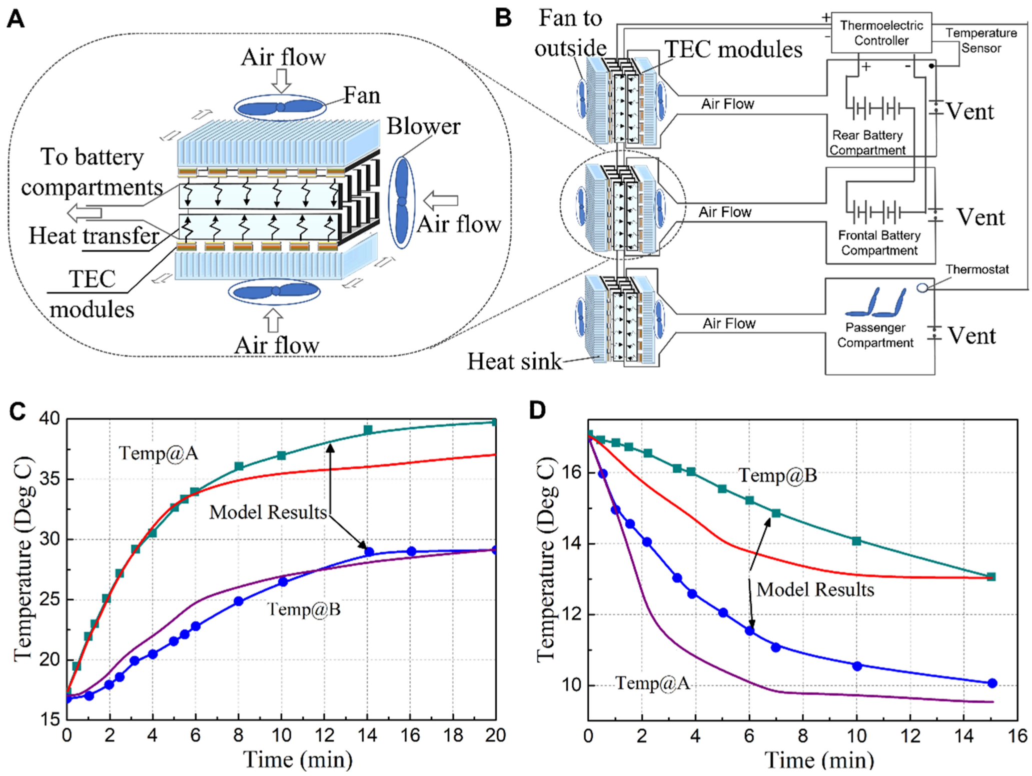

Figure 4. TEC-based BTMS module and performance testing: (A) Configuration of the basic thermal unit setup; (B) Block diagram of the thermal management system; (C) Heating test at 4 Amps; (D) Cooling test at 10 Amps. Temp@A refers to the temperature at the hose system and near the TEC. Temp@B refers to the temperature at the bottom end of the front battery[55]. TEC: Thermoelectric cooler; BTMS: battery thermal management system.

methods, such as air cooling, liquid cooling, PCM cooling, and heat pipe cooling, to integrate their respective advantages and enhance the overall thermal management efficiency of the system.

BTMS 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[60,61]. Alaoui proposed a TEC-BTMS system that incorporates forced air cooling[32]. 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 aluminum plate. 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[32]. In 2017, Alaoui designed a TEC-BTMS 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 center of the battery pack, applied to lithium-ion batteries recovered from electric vehicles [Figure 5B][62]. The BTMS

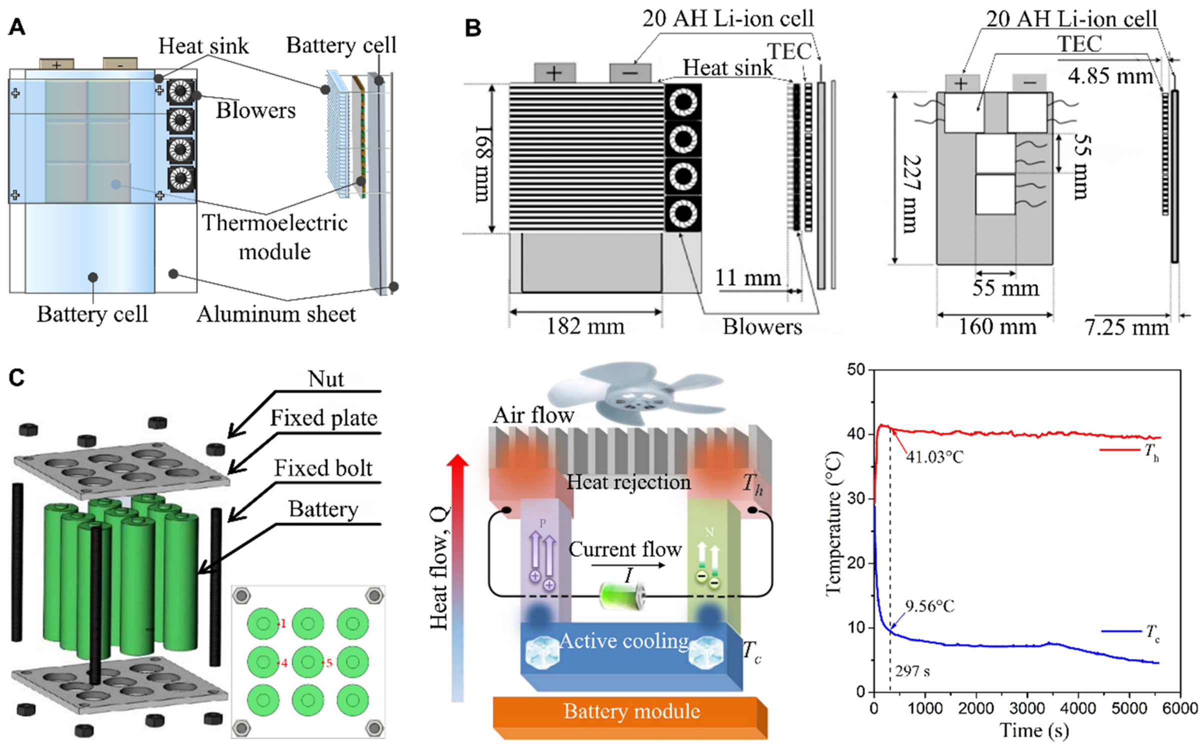

Figure 5. TEC-based BTMS combined with air cooling: (A) Schematic diagrams of BTMS integrating TEC and forced air cooling[32]; (B) Physical assembly includes Li-ion battery cells, TEC modules, heatsink, and blowers. Reprinted with permission[62]. Copyright 2017, Elsevier; (C) 3D diagram illustrating the battery module and temperature measurement points; temperature-time diagram of the cold and hot sides of TEC. Reprinted with permission[63]. Copyright 2019, Hindawi. TEC: Thermoelectric cooler; BTMS: battery thermal management system.

aimed to keep the battery pack within the appropriate temperature range while minimizing the additional power required to drive the system. 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 consumption, it resulted in higher battery surface temperatures. This accelerated battery aging and approached the safety temperature limit.

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][63]. 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. Secondly, the generated heat was then 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 3C 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.

BTMS based on TEC and liquid cooling

Liquid cooling systems use a liquid with high thermal conductivity as a medium to directly or indirectly dissipate the heat generated by the battery. In the design of liquid cooling structures, the battery is either directly immersed in the cooling liquid for heat dissipation or heat is transferred indirectly through a cooling plate. Indirect cooling involves transferring the heat generated by the battery to a cooling plate, which then dissipates the heat to the liquid[64,65]. Liquid cooling is currently the mainstream method for BTMS cooling due to its high thermal conductivity and efficient cooling capability, making it suitable for overall heat dissipation of high-power battery packs and improving temperature consistency within the battery pack. However, liquid cooling systems face challenges such as localized overheating, complex structure, and thermal safety of high-power batteries. Therefore, further research and optimization are needed in the design and thermal safety aspects of liquid cooling systems[66,67].

The combination of TEC and liquid cooling in BTMS offers multiple advantages including efficient heat dissipation, precise temperature control, energy efficiency, environmental friendliness, safety, and adaptability, making it one of the important directions for the future development of thermal management technology in areas such as electric vehicles[57,68]. Liu *et al.* introduced a novel BTMS integrating TEC (TEC1-12703, L × W × H is 40 mm × 40 mm × 5 mm) with liquid cooling and experimentally calibrated the model[37]. Figure 6A depicts the physical model with eight battery cells of 100 Ah, each composing the battery pack in the BTMS. The TEC's cold side is mounted on the battery cells to absorb their heat, while its hot side is connected to a water jacket for effective heat dissipation. Eighteen pairs of thermocouples are placed on the battery surfaces, with nine pairs on each side. Figure 6B shows the temperature distribution of the eight batteries with only liquid cooling, where the average surface temperatures of the first, last, and other batteries are 315.7, 318.9, and 318.3 K, respectively. Figure 6C illustrates the temperature distribution of the batteries with TEC combined with liquid cooling, with average surface temperatures of 312.2 K for the first battery, 311.4 K for the last, and 311.5 K for the others. The results demonstrate that TEC cooling effectively reduces battery temperatures to below 313 K, achieving an average temperature variation of less than 1 K, which is significantly lower than the scenario without TEC cooling. Troxler *et al.* investigated the influence of artificially induced temperature gradients on battery performance, utilizing TEC to create and sustain temperature gradients in lithium-ion batteries under both isothermal and non-isothermal conditions, rather than directly cooling the batteries[69]. The study found that batteries maintained at temperature gradients exhibited lower impedance characteristics compared to those maintained at theoretical average temperatures. This phenomenon is attributed to the fine design of the battery's internal structure and the nonlinear temperature-dependent nature of charge transfer resistance.

Liu *et al.* conducted experiments on the cooling effect based on TEC (TEC-12706, L × W × H is 30 mm × 30 mm × 3.5 mm, the refrigerator power is 60 W and the maximum current is 4.3 A) combined with liquid cooling, with the experimental setup consisting of thermoelectric units and cooling plates [Figure 7A][70]. The cold side of the thermoelectric unit is connected to the bottom of the battery, while the hot side is

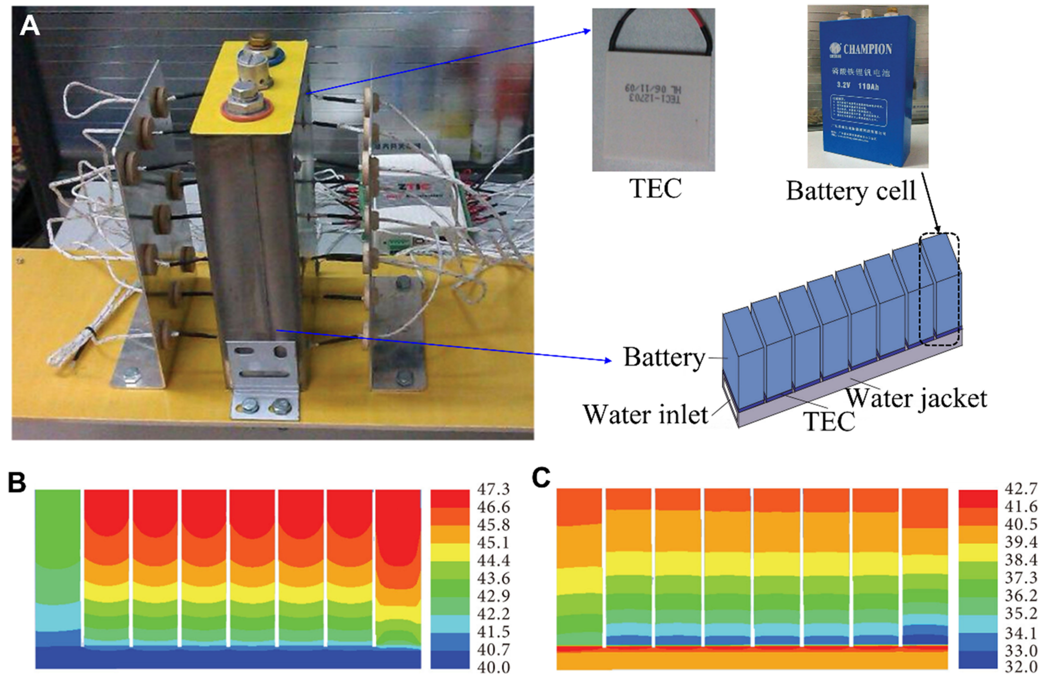

Figure 6. TEC-based BTMS combined with liquid cooling: (A) Configuration of BTMS employing TECs in conjunction with liquid cooling, and 3D depiction of the battery cell pack; (B) Temperature distribution utilizing water cooling; (C) Temperature distribution with TEC and water cooling. Reprinted with permission[37]. Copyright 2014, Sage Publication Ltd. TEC: Thermoelectric cooler; BTMS: battery thermal management system.

connected to the cooling plate. Four battery cells were selected, with the TEC cooling unit's current controlled by a DC power supply, and the coolant inlet temperature maintained constant using a thermoelectric water bath. Multiple temperature monitors were used to monitor battery temperature data, with five thermocouples placed at the intersection point of the four battery cells and across the entire battery surface. The cooling performance was studied by varying coolant flow rate, ambient temperature, discharge rate, and TEC operating voltage, with systematic optimization of the operating current of each TEC component throughout the process to achieve optimal cooling performance at minimum power consumption. The results showed that increasing the coolant flow rate or decreasing the coolant temperature effectively reduced the average module temperature.

Subsequently, to address the low charging efficiency of the traction battery in cold weather, they designed a new BTMS based on TEC and liquid cooling, with TECs included at the bottom and top of the system [Figure 7B][71]. The effects of various TEC operating voltages on basic preheating performance and system power consumption were analyzed using the experimental platform system. The research findings are as follows: (1) Battery capacity has a strong dependency on ambient temperature within a certain range; (2) Increasing TEC voltage reduced heating time but resulted in higher temperature differentials and power consumption; (3) The power consumption of electronic fans has a significant impact on heating time and temperature differentials.

An *et al.* proposed a dual-active BTMS (DA-BTMS) that harmoniously integrates liquid cooling and TEC (L × W × H is 40 mm × 40 mm × 0.8 mm) cooling principles [Figure 7C], consisting of four pouch cells, an aluminum housing, an insulation board, TECs, and liquid cooling plates[72]. The DA-BTMS features an aluminum alloy module housing designed to accommodate four battery cells, with aluminum-made battery

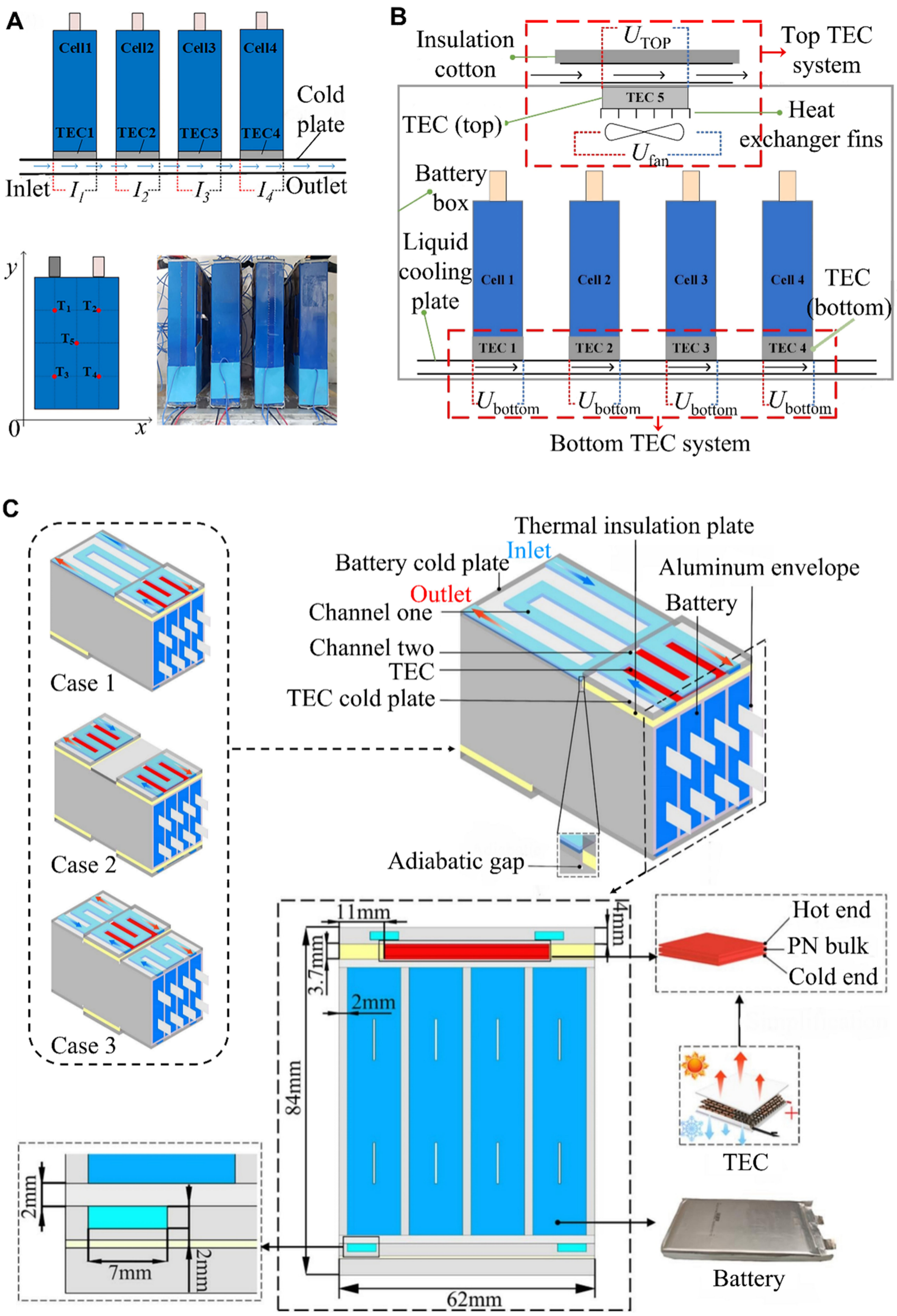

Figure 7. TEC-based BTMS combined with liquid cooling: (A) Installation illustration of BTMS system integrating TEC and liquid cooling, along with temperature measurement points. Reprinted with permission[70]. Copyright 2020, WILEY-VCH; (B) Schematic representation of BTMS system incorporating TEC and liquid cooling. Reprinted with permission[71]. Copyright 2023, Elsevier; (C) BTMS integrating liquid cooling with TEC, depicting various configurations of the BTMS. Reprinted with permission[72]. Copyright 2024, Elsevier. TEC: Thermoelectric cooler; BTMS: battery thermal management system.

cold plates and TEC cold plates stacked on the top and bottom of the housing, respectively. The placement and quantity of TECs within the DA-BTMS significantly influence its cooling capabilities. Three different DA-BTMS configurations were designed based on the number and position of TECs: Case 1 features two TECs arranged diagonally, Case 2 has four TECs in a symmetrical layout, and Case 3 includes two TECs symmetrically positioned. Through numerical simulations and physical experiments, the three different TEC layouts were compared to determine the optimal configuration. The effects of input current to the TEC and coolant mass flow rate on battery cooling were also studied. Additionally, the capability of TEC to function interchangeably as both a heating and cooling element allows for battery preheating in cold conditions by reversing the current flow. Experimental outcomes revealed that, when subjected to a 2C discharge rate and an ambient temperature of 313 K, the DA-BTMS equipped with sole liquid cooling efficiently regulated temperature within the targeted range, optimizing performance at a coolant mass flow rate of 0.59 $g \cdot s^{-1}$. Even at a discharge rate of 3C, the DA-BTMS could reliably maintain system operation with TEC-assisted cooling. In environments with excessively high temperatures of 323 K, the system demonstrated a remarkable reduction in peak temperature, plummeting from 323 to 315.32 K at a 2C discharge rate and with an optimal TEC input current of 1.6 A. This reduction is attributed to the potent refrigeration effect of the TECs. This system not only enhances the spatial efficiency of the battery pack but also keeps the maximum temperature of the battery modules within acceptable limits, resiliently adapting to both harsh hot and cold environmental conditions, effectively saving energy compared to traditional pure TEC cooling methods.

BTMS based on TEC and PCM cooling

The PCM-based BTMS (PCM-BTMS) is a passive thermal management system that utilizes PCM to store and release latent heat, maintaining the battery pack at optimal temperatures without consuming energy, having moving parts, and with low maintenance costs. In high-temperature environments, PCM undergoes a phase transition and stores the heat generated during battery discharge in the form of latent heat, thus offering significant advantages in maintaining uniform battery surface temperatures[58,73-76]. Hallaj and Selman were the first to apply PCM to electric vehicles, demonstrating that integrating PCM resulted in better battery temperature uniformity compared to batteries without PCM integration[77]. However, phase change processes are prone to issues such as volume changes, container corrosion, and liquid leakage. The cooling effect generated by solid-state TECs can prevent PCM from becoming oversaturated.

Song *et al.* developed a BTMS by integrating TEC and PCM devices [Figure 8A][38]. The battery pack, rated at 48 V and 80 Ah, consisted of 60 cells arranged in a configuration of 4 cells in parallel and 15 cells in series. PCM was strategically positioned underneath and around the battery module, filling the aluminum casing to stabilize the temperature field of the battery. This design not only enhanced heat transfer efficiency between PCM by utilizing the aluminum casing but also provided structural support for the battery module. TECs (40 mm × 40 mm × 2.5 mm) were attached to the surface of the aluminum casing, with aluminum fin heat sinks connected on the other side to enhance heat transfer further. Additionally, ten monitoring points were identified on the distribution map, all located at the center of the corresponding surfaces for precise monitoring of temperature changes in the battery pack. Results indicated that the TEC and PCM-based BTMS maintained the optimal temperature range for outdoor backup battery packs for 4.4 days after cooling once in a 323 K environment and for 3.52 days after heating once in a 263 K environment. Furthermore, compared to other configurations, distributing the semiconductor thermoelectric devices on both sides of the minimum size direction wings improved temperature uniformity and insulation time. The results showed that the standby battery pack, equipped with TEC and PCMs, maintained stable cooling and heat preservation across various temperatures, effectively prolonging battery life.

Liao *et al.* designed a BTMS integrating TEC and PCM to meet the cooling, heating, and thermal insulation requirements of lithium-ion batteries[51]. The geometric model [Figure 8B], includes 16 individual battery cells, a cylindrical PCM casing, a honeycomb-like thermal conduction framework, a heat conduction plate, two TECs (40 mm × 40 mm × 2.5 mm, maximum working current 3 A), and heat sinks. The heat sinks enhance heat transfer between the TECs and the external environment, while the honeycomb-like thermal

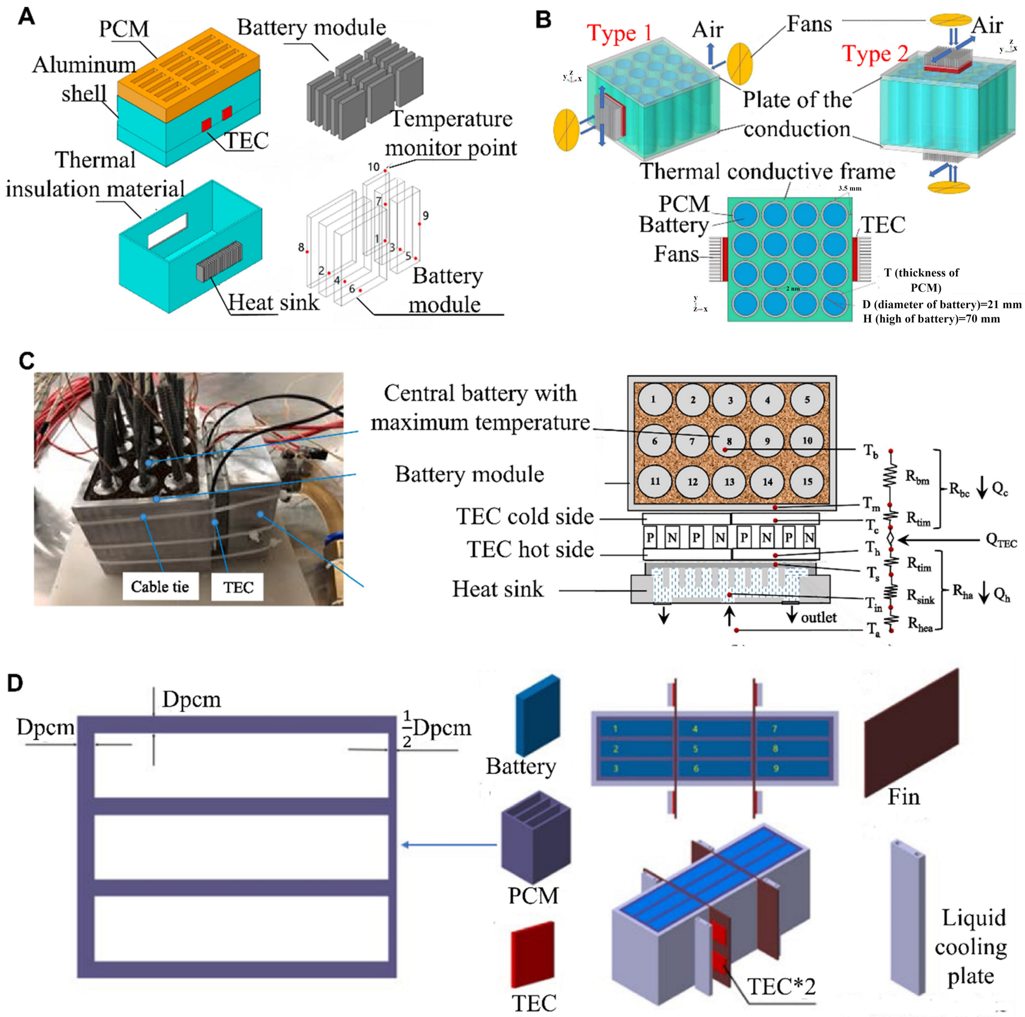

Figure 8. TEC-based BTMS combined with PCM cooling: (A) Diagram illustrating the battery pack with TEC and PCMs. Reprinted with permission[38]. Copyright 2018, Elsevier; (B) Geometric dimensions of the full-temperature BTMS. Reprinted with permission[51]. Copyright 2021, Elsevier; (C) Configuration of TEC and schematic of the battery module containing 3 × 5 batteries integrated with TEC, accompanied by the corresponding thermal resistance network. Reprinted with permission[78]. Copyright 2019, Elsevier; (D) Geometric model of BTMS. Reprinted with permission[39]. Copyright 2022, Elsevier. TEC: Thermoelectric cooler; BTMS: battery thermal management system; PCM: phase change material.

conduction framework and heat conduction plate strengthen heat conduction, encapsulate the PCM, and facilitate TEC installation. The geometric model of the BTMS was constructed using SolidWorks and then imported into COMSOL Multiphysics for mesh generation and numerical calculations. To enhance cooling, the study analyzed the effects of thermal conduction framework material types, heat exchanger layout types, and phase change cold storage module configurations on heat exchanger performance. For low-temperature preheating, the study analyzed the effects of insulation material settings and the quantities of TECs and PCM. Finally, the study investigated the influence of PCM types on the post-discharge thermal protection efficacy of battery modules. The findings revealed that in high-temperature environments with high-rate (3C) discharge, the synergetic utilization of composite PCM (CPCM) and TECs effectively maintained the peak battery temperature below 318.15 K, with a maximum temperature disparity of 3 K across the module, while preheating limited the temperature difference to 5 K.

Jiang *et al.* investigated the thermal performance of TEC (TEC1-12710, dimension is 50 mm × 50 mm × 3.3 mm, the refrigerator power is 94.2 W and the maximum current is 10 A) in cylindrical battery module thermal management[78]. The experimental setup involved a 3 × 5 array of 18,650 test batteries embedded in foam copper infused with organic PCM to enhance heat transfer [Figure 8C]. In experimental testing, this arrangement aimed to evaluate and compare the transient and steady-state thermal performance of TECs with natural convection and liquid cooling methods, providing insights into the efficiency of TECs in regulating battery temperatures. The optimal current obtained in experiments, considering the highest cooling power and lowest battery temperature, was approximately 6.0 to 6.5 A[78]. Further analysis revealed that the thermal resistance on the hot side had a greater impact on the optimal current compared to that on the cold side. Additionally, the study found that enhancing the number of thermoelectric arms by narrowing the spacing between them effectively improved the *COP* of the TEC module.

Liu *et al.* elucidated the implementation strategy of a hybrid active-passive BTMS utilizing heat sinks to optimize the integration of TECs (L × W × H is 44 mm × 44 mm × 3.7 mm, the refrigerator power is 50 W, and the maximum current is 6.4 A) and PCMs [Figure 8D][39]. The cold side of the TEC generates cooling to the PCM, slowing its melting process and thereby prolonging the temperature control period. Heat sinks play a crucial role in transferring the accumulated heat from the PCM to the cold side of the TEC, enabling effective cooling of the batteries in high-temperature environments. Numerical simulations were performed to evaluate the influence of different heat sink thicknesses (ranging from 2 to 8 mm) and different TEC input currents (1-6 A) on thermal management performance. The results revealed that increasing the heat sink thickness from 2 to 8 mm extended the temperature control duration by 12%, but also raised the temperature difference by 13.7%. As the current increased from 1 A to 6 A, the temperature control duration improved by 87.42%, though this came at the cost of a greater temperature difference and a reduction in *COP*. Considering factors such as temperature control duration, temperature difference, and *COP*, it was found that the BTMS model constructed with a 4 mm thick heat sink and a 3 A TEC input current exhibited optimal performance.

BTMS based on TEC and heat-pipe cooling

Thermal pipes are widely utilized in the energy industry for their exceptional heat transfer efficiency, attributed to their high thermal conductivity and low thermal resistance. They find extensive applications in aerospace, defense, microelectronics cooling, construction materials, metallurgy, solar energy, and other fields[79,80]. Due to their adaptable design, thermal pipes can efficiently remove a large amount of heat from within battery packs, maintaining batteries within the desired operating temperature range. They can substantially minimize temperature differentials within the battery pack. Research has shown that BTMSs incorporating thermal pipes can significantly lower the peak temperature rise in battery packs and temperature differentials between batteries. Yuan *et al.* utilized thermal pipes as the primary heat transfer component in a BTMS, supplemented with heat collectors and radiators, to analyze the factors influencing battery pack temperature and the related mechanisms[81]. The results demonstrated that the BTMS utilizing thermal pipes effectively suppressed battery temperature increases. Smith *et al.* proposed a high-power BTMS based on thermal pipes, which exhibited superior temperature uniformity and enhanced system safety compared to traditional liquid cooling systems[82]. Gan investigated a thermal pipe-based BTMS for cylindrical battery modules and found that, compared to natural air-cooled BTMS, the battery temperature could be significantly lowered by 287 K at a discharge rate of 5C[83].

Sun *et al.* devised a scheme integrating gravity-assisted heat pipes (GAHP) with a TEC (TEC-12708, L × W × H is 40 mm × 40 mm × 5.4 mm, the refrigerator power is 81 W, and the maximum current is 8.5 A) system for electronic device cooling [Figure 9A][79]. Heat sinks were mounted on the cold side to enhance the absorption from the thermoelectric plates. A flat and smooth evaporative surface was utilized in the

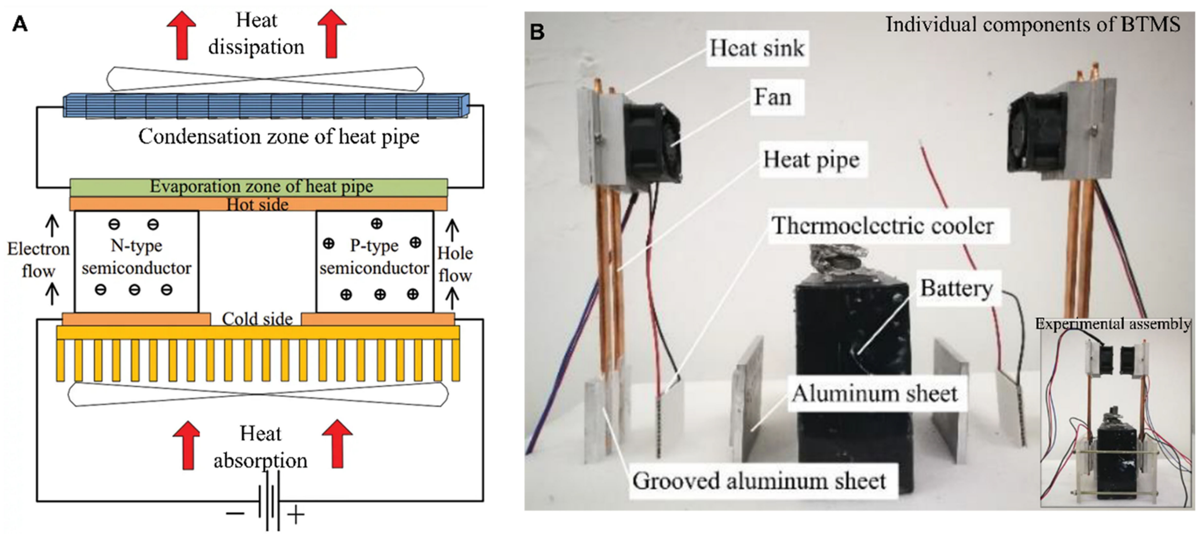

Figure 9. TEC-based BTMS combined with heat-pipe cooling: (A) Schematic representation of a TEC system integrated with GAHP. Reprinted with permission[79]. Copyright 2017, Elsevier; (B) Hybrid BTMS incorporating a heat pipe with a TEC. Reprinted with permission[84]. Copyright 2020, MDPI. TEC: Thermoelectric cooler; BTMS: battery thermal management system; GAHP: gravity-assisted heat pipes.

GAHP, installed on the hot side of the thermoelectric module, to minimize contact thermal resistance. Fans were placed above the heat sink at the cold side of the thermoelectric module and in the condensation region of GAHP to lower the temperature of electronic devices and blow heated air into the surrounding environment. When DC power was applied, the TEC absorbed heat from the heat sink and transferred it to the hot side of the thermoelectric module. The results show that the TEC system with GAHP has a maximum cooling capacity of approximately 220 W, compared to 140 W for the TEC system with a heat sink. This indicates the GAHP-enhanced cooling capacity by around 73.54% and reduced energy consumption by 42.20% compared to TEC systems with air-cooled heat sinks, while maintaining the same cooling effect.

Zhang *et al.* proposed a BTMS for prismatic lithium batteries that combines TEC (working current was 3.96 A, the corresponding voltage was 7.8 V, and the power was 17.92 W) with heat pipes[84]. The structure of the BTMS with heat pipes is illustrated in Figure 9B, where the cold and hot sides of the TEC are attached to the aluminum plate and heat pipes, respectively. The heat generated at the hot side of the TEC is transferred to the heat sink via the heat pipes. Aluminum plates and slotted aluminum plates are placed on the surfaces of the battery and heat pipes to obtain a more uniform temperature distribution, followed by accelerated cooling using fans. Numerical simulations and discharge experiments were performed to study the cooling performance of the hybrid BTMS at different discharge rates. Results showed that at a discharge rate of 1C, the battery surface temperature remained below the optimal operating temperature without the need for any additional cooling measures. At a discharge rate of 1.5C, the heat pipe-based BTMS met the optimal operating temperature. However, at discharge rates of 2C, 2.5C, and 3C, the hybrid BTMS with heat pipes and TEC required cooling the battery to within 318 K.

TEC-based multi cooling systems

The use of a single cooling method often cannot fully meet the cooling requirements of battery packs. Composite cooling combines multiple individual cooling methods, integrating the advantages of each, resulting in better cooling performance and temperature uniformity compared to single cooling methods[85-88].

Lyu *et al.* developed a hybrid BTMS consisting of liquid, air, and TEC to cool simulated thermal loads[57]. In this system, a cylindrical thermal load, encapsulated in a copper housing, suspends lithium-ion battery cells in a water tank, cooled by a TEC system, and further by fans [Figure 10A]. By supplying a constant voltage of 40 V to the heating module and 12 V to the TEC device, the heating module simulated a 1C discharge rate of lithium-ion cells for one hour. After completing the thermal load test, the simulated lithium-ion cell surface temperature dropped from 328 to 285 K, achieving a significant temperature reduction. Luo *et al.* developed a novel BTMS integrated with TEC and PCM, employing a fin framework to improve heat transfer [Figure 10B][89]. They developed a transient thermal-electric-flow multi-physics numerical model to comprehensively analyze the system's thermal. The results showed that increasing the TEC input current, as well as the length and thickness of the fins, effectively lowered the maximum temperature and PCM liquid fraction.

Lyu *et al.* proposed a novel battery pack design integrated with a BTMS, which includes a combination of TEC with liquid and air circulation [Figure 10C][90]. The heat produced by the battery pack is transferred to the cold side of the TEC and subsequently dissipated into the surrounding environment through a heat sink. Results indicated that the voltage values of the blower and pump significantly affect the performance of the cooling system. Performance validation of the BTMS was conducted using simulated battery packs. For the 40 V test, the TEC-based BTMS reduced the battery pack temperature by approximately 20 K compared to pure liquid cooling. During the 30 V power supply test, the battery pack temperature remained below 303 K for 5,000 s. Furthermore, under continuous discharge conditions with a 50 V input, the battery pack temperature remained below 333 K for 3,000 s, which is considered an extreme condition for battery operation.

Luo *et al.* developed a BTMS integrating TEC with both water and air cooling [Figure 11A], and established a coupled thermal-electric-fluid multi-physics model to assess the system's thermal performance[68]. Their numerical simulations investigated the effects of various cooling parameters, such as TEC input current, air convective heat transfer coefficient, and cooling water flow rate. Results indicated that introducing TEC into battery thermal management can enhance cooling capacity compared to conventional air and water cooling methods. The cooling power and *COP* of the TEC increased first and then decreased with rising input current. Optimal thermal performance was achieved with an air convective heat transfer coefficient of 50 $W \cdot m^2 \cdot K^{-1}$, a water flow rate of 0.11 $m \cdot s^{-1}$, and a TEC input current of 5 A, resulting in the highest temperature and temperature difference of 302.27 and 3.63 K, respectively. Nevertheless, these cooling parameters are interrelated, and selecting appropriate cooling parameters is crucial for balancing the thermal performance and energy consumption of the BTMS. Chang *et al.* developed a TEC-based BTMS designed to ensure high-temperature uniformity for space lithium-ion batteries[91].

Figure 11B illustrates the traditional thermal management approach, which employs a single-phase fluid loop for cooling and electric heaters for heating. In this system, the waste heat from the lithium-ion battery pack (LIBP) is absorbed by a cold plate positioned beneath the LIBP and transferred via the fluid loop to a satellite radiator. The radiator then releases heat into space, effectively cooling both the LIBP and other satellite components. When the LIBP temperature drops, it is heated by the electric heater. Overall, the integration of the single-phase fluid loop and electric heaters maintains the LIBP temperature within a desirable range. The TEC-based high-temperature uniformity BTMS features a setup with 16 lithium-ion batteries, a battery mounting base, 16 TECs, 32 TEC heat transfer blocks (either cold or hot side), a cold plate heat exchanger, insulation material, and a battery pack outer casing, along with control unit and drive

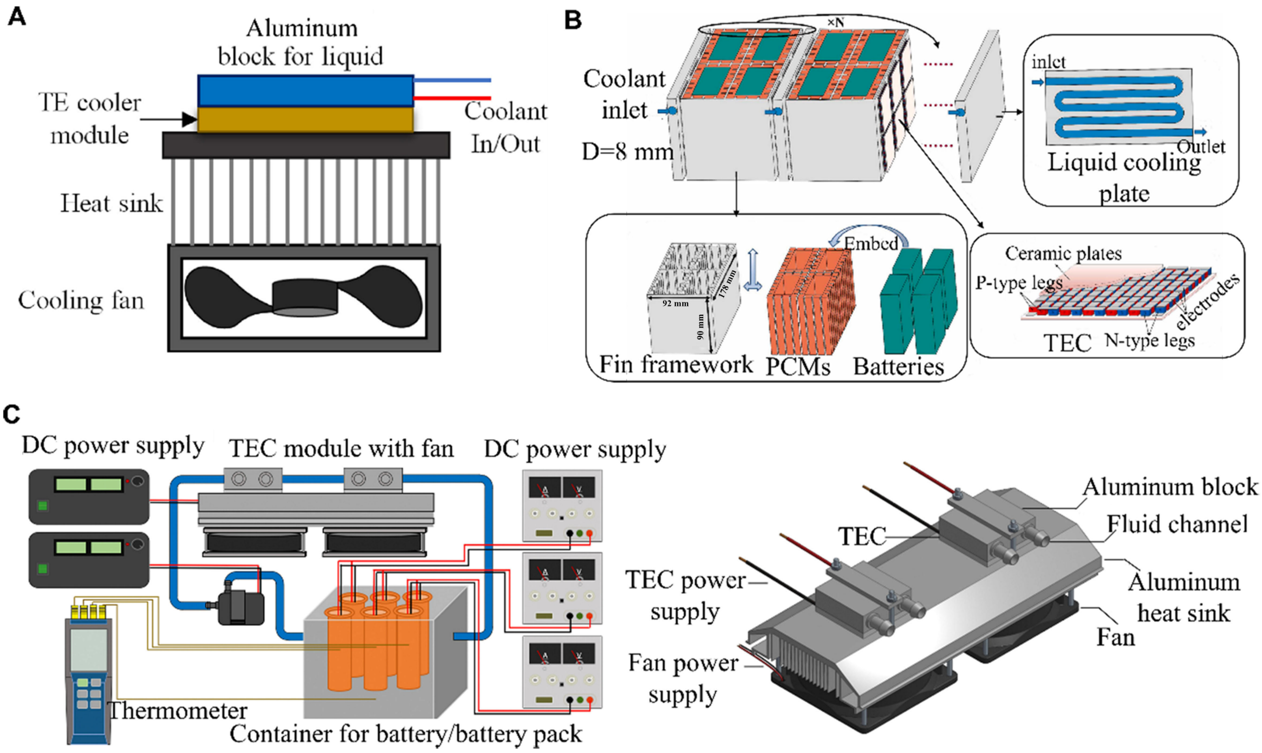

Figure 10. TEC-based hybrid BTMS: (A) Schematic depiction of the single unit of the TEC system utilized for BTMS. The TEC module design integrates a heat sink, forced air cooling, and liquid cooling. Reprinted with permission[57]. Copyright 2019, Elsevier; (B) Schematic representation of the BTMS integrated with TEC, PCM, and a fin framework. Reprinted with permission[89]. Copyright 2024, Elsevier; (C) Overview schematic of the experimental setup, demonstrating the integration of a battery pack with a BTMS incorporating TEC in combination with liquid and air circulations. Reprinted with permission[90]. Copyright 2021, Elsevier. TEC: Thermoelectric cooler; BTMS: battery thermal management system; PCM: phase change material.

unit. By adjusting the driving current of the 16 TECs through a dual-layer coordinated controller and changing the direction of the current on the TECs, cooling and heating services can be provided to the lithium-ion batteries, thereby regulating the temperature of the LIBP. Results indicate that this method effectively keeps the LIBP's average temperature within the optimal temperature range of 15 to 308 K under complex thermal disturbances, with a maximum temperature difference of 1.7 K, 76.7% lower than uncontrolled conditions, and a minimum temperature difference of only 0.06 K. This temperature control strategy significantly improves the temperature adaptability of LIBPs for space applications, contributing to further enhancing their operational performance and reliability.

BTMS based on flexible TEC

Flexible TECs are engineered to meet the demands of complex operational environments and provide localized heat dissipation. Applications include wearable devices, localized cooling systems, and personal temperature regulation systems[92]. Advances in these technologies have demonstrated the significant potential of flexible thermoelectric cooling for localized heat management. There are generally two approaches to introduce mechanical flexibility into thermoelectric devices: one involves encapsulating low-thickness inorganic thermoelectric materials in elastomers and connecting them with flexible electrodes, such as silver, copper, and conductive polymers[93], often achieved through vapor deposition or inkjet printing onto soft polymer or plastic substrates[94]. In this approach, materials such as $Bi_2Se_{0.3}Te_{2.7}$[95], $Bi_{0.5}Sb_{1.5}Te_3$[95], and Bi_2Te_3/Sb_2Te_3 superlattices[96], which exhibit ZT values greater than 1 at room temperature, show considerable promise. Polyimide (PI) is commonly used as a flexible substrate due to its low thermal conductivity, high mechanical strength, and excellent tensile properties[95]. The second

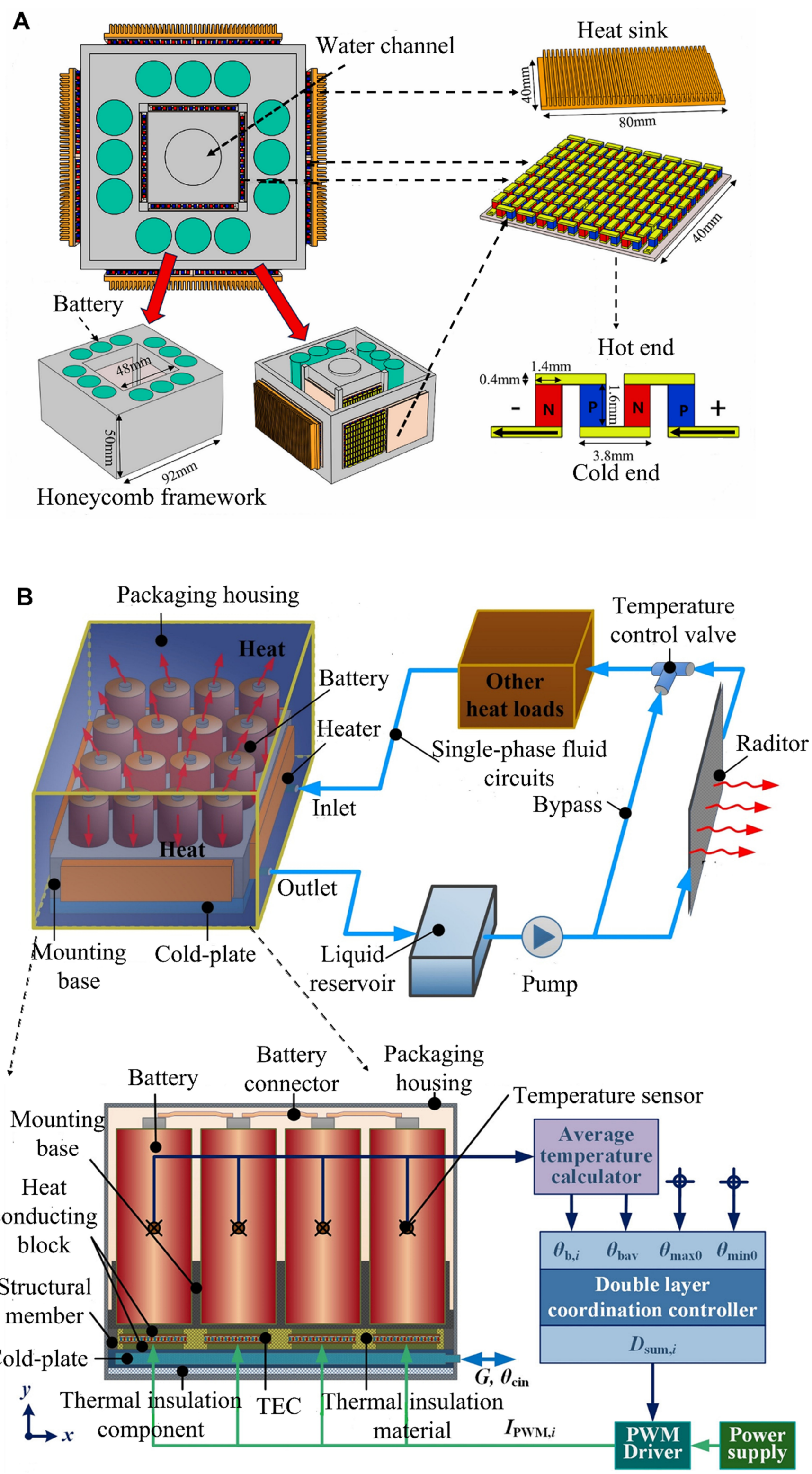

Figure 11. TEC-based hybrid BTMS: (A) Schematic representation of TEC-based BTMS coupled with water cooling and air cooling. Reprinted with permission[68]. Copyright 2024, Elsevier; (B) Composition structure and working principle of TEC-based thermal management. Reprinted with permission[91]. Copyright 2022, Elsevier. TEC: Thermoelectric cooler; BTMS: battery thermal management system.

approach involves using material systems with inherent mechanical flexibility, such as poly(3,4-ethylene dioxythiophene)(styrene sulfonate) (PEDOT:PSS), poly(3-ethylthiophene) (P3HT)[97], and two-dimensional materials such as silver sulfide (Ag_2S)[98].

Despite the clear advantages of flexible thermoelectric cooling technology in enhancing device flexibility and comfort, its application in BTMS remains limited. Current research primarily focuses on the fundamental properties of flexible thermoelectric materials and their use in wearable devices. For example, Ding *et al.* developed a flexible PCM radiator that combines polyamide, graphene, and silicone rubber, and applied it to TECs[92]. This TEC can lower body temperature by 11.21 K within 30 s and maintain the reduced temperature for at least 300 s, effectively enhancing the heat dissipation performance of TECs. Zhang *et al.* designed a wearable TEC with a dual-layer heat dissipation unit composed of hydrogel and nickel foam, which demonstrated excellent flexibility[99]. When operated at an input current of 0.3 A, it achieved a significant and sustained temperature drop of approximately 10 K. In practical tests, the device using AA batteries achieved a stable temperature reduction of 7 K. Wei *et al.* designed a flexible heat dissipation system for a pin-fin soft-cover wearable device. This system simultaneously achieves power generation and cooling effects[100]. As a TEG, it delivers a power density of 6.63 $\mu W \cdot cm^{-2}$ on a stationary human body at an ambient temperature of 293 K. As a cooler, it can lower the skin temperature by 1.5 K. Mukaida *et al.* designed and fabricated a polymer-based thermoelectric module for charging lithium-ion batteries[101]. A 5-gram device can fully charge a commercial lithium-ion battery (Nichicon SLB03070LR35) within two days. Further investigation and validation are needed to fully realize the potential of flexible thermoelectric cooling technology in BTMS.

CONCLUSION AND OUTLOOK

Effective battery thermal management technology is essential for the widespread adoption of lithium-ion batteries, with future trends in BTMS cooling technology expected to emphasize improved efficiency, environmental friendliness, and cost-effectiveness. An efficient BTMS should possess high precision, real-time predictability, and controllability of states. Existing simulation software provides robust support for the development of battery thermal management technology. TECs used for battery thermal control represent a new competitor in the realm of electric vehicles. TECs operate by converting voltage into temperature differences, and temperature can be easily regulated by changing the direction of current flow. TECs offer advantages such as relative quietness, stability, and reliability, and they have begun to emerge in prominence within power BTMS. However, their cooling efficiency is relatively low, necessitating their combination with other technologies. Based on the discussion of air cooling, liquid cooling, PCM cooling, heat pipe cooling, and composite cooling technologies utilizing thermoelectric refrigeration, the following conclusions and prospects can be drawn:

1. Combining TEC with air cooling: BTMS utilizing thermoelectric refrigeration combined with air cooling can effectively address the issue of uneven temperature distribution among battery cells in air cooling technology. This integration enhances the system's heat dissipation efficiency, stability, and energy utilization, offering the potential to drive advancements in electric vehicles, electronic devices, and other fields.

2. Combining TEC with liquid cooling: BTMS based on thermoelectric refrigeration combined with liquid cooling offers the advantages of precise temperature control through TEC while maintaining the high thermal conductivity and cooling efficiency of liquid cooling. This integration enables a more streamlined and compact liquid cooling system, reducing reliance on complex structures and components, and thereby lowering assembly and maintenance costs. It also enhances system reliability and stability by effectively

addressing localized overheating issues in liquid cooling systems, all while promoting energy efficiency and environmental sustainability.

3. Combining TEC with PCM: PCMs are capable of absorbing or releasing significant amounts of latent heat during phase transitions, which helps keep the battery pack stable within the optimal temperature range. However, PCMs undergo volume changes during phase transition, and some PCM materials may corrode container materials. Thermoelectric refrigeration modules can provide additional cooling effects when needed, preventing PCM melting due to oversaturation of energy storage. This helps extend temperature control time and improve system stability.

4. Combining TEC with heat pipe cooling: heat pipes exhibit high thermal conductivity and flexible shapes, enabling rapid heat transfer to the heat dissipation area, but they have limited capacity and contact area. Thermoelectric refrigeration technology can achieve precise temperature control in specific areas as needed. When combined with the fast heat transfer capabilities of heat pipe technology, temperature control becomes faster and more precise, ensuring equipment operates at its optimal working temperature.

5. Hybrid refrigeration system based on TEC: coupling TEC technology with other cooling techniques in a BTMS allows for the full utilization of the advantages of each technology, achieving more efficient thermal management and temperature control. Moreover, it enables the flexible selection of suitable thermal management solutions based on the characteristics of different cooling techniques to meet diverse user requirements.

With the increasing requirements for electric vehicle batteries, their energy density is gradually increasing. The development of future BTMS will be influenced by factors such as the actual use of electric vehicles, operating environments, different system performance, and economic characteristics. The combination of TEC-based BTMS cooling technology with other cooling techniques will become more widespread. However, TEC-based BTMS face several limitations, including efficiency constraints, power consumption issues, thermal management challenges, and cost considerations. In the future, we may see the emergence of more novel cooling technologies that integrate with TEC technology, further enhancing the efficiency and performance of BTMS. According to demand, BTMS can be developed into multiple integrated subsystems, considering the characteristics of each system to promote practical applications better. Designing more reliable, safer, and energy-efficient TEC-based BTMS remains a key direction for future development, which can be approached from the following aspects. The main strategies include improving efficiency, reducing costs, flexibilization of integrated systems and market expansion:

1. Improving efficiency:
(1) Thermoelectric material development: currently, the challenge for commercially viable thermoelectric cooling technologies is the high cost of thermoelectric materials. Bismuth telluride-based materials are among the most commonly used commercially available materials, yet their manufacturing costs remain high. Therefore, it is crucial to develop new thermoelectric materials or fabrication techniques to reduce manufacturing costs.
(2) Module design optimization: enhance the design of TECs by optimizing the structure and arrangement of thermoelectric modules to maximize thermoelectric efficiency.
(3) Advanced thermal management: implement advanced thermal management technologies, such as efficient heat exchangers or thermal interface materials, to reduce heat losses and improve overall system efficiency.
(4) System integration: integrate TECs with other cooling technologies to achieve higher overall efficiency.

Additionally, designing more effective heat dissipation systems to address heat accumulation during extended high-load operations is also a key task.

2. Reducing costs:
(1) Scaling production: achieve economies of scale by expanding production capacity, which can reduce unit costs.
(2) Process optimization: improve manufacturing processes and material use to minimize waste and unnecessary costs during production.
(3) Standardized components: utilize standardized and modular designs to lower production complexity and costs.
(4) Research and development investment: increase investment in research and development to drive technological innovation and reduce long-term costs.

3. Flexibilization of integrated systems:
In order to enhance wearability, many new types of batteries are designed to be flexible and compact. To integrate with such batteries, TEC systems also need to be designed with a certain degree of flexibility. This is also the direction of development for future wearable electronic devices such as e-skin.

4. Market expansion:
The key to expanding the market is to apply BTMS based on TEC technology to more fields, including healthcare, outdoor activities, clothing, and accessories. By providing users with personalized temperature regulation functions on the go, market share can be expanded, and costs reduced, achieving the commercialization and popularization of the technology.

Overall, although TEC-based BTMS technology has limitations in some aspects, with continuous improvement of the technology and expansion of application areas, it is expected to become one of the important technologies in the field of thermal management in the future.

DECLARATIONS

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Authors' contributions

Initiated the idea: Wang L, Shi XL, Chen ZG
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All authors have read the manuscript and approved the final version.

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Conflicts of interest
Chen ZG is an Editorial Board Member of the journal *Soft Science* and a Guest Editor of the special issue; Dong C is affiliated with SINOPEC (Dalian) Research Institute of Petroleum and Petrochemicals Co., Ltd.; the other authors have declared that they have no conflicts of interest.

Ethical approval and consent to participate
Not applicable.

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Not applicable.

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