Thermal Management Systems for Li-Ion Batteries Used in Electric Vehicles

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Received 10th May 2024
Revised 26th May 2024
Accepted 27th May 2024

Keywords
Li-ion battery,
Battery Thermal management systems, Phase Change Material, Air Cooling, Electric vehicle.

Abstract
Rechargeable Li-ion batteries (LIBs) have considerably advanced in enabling electric vehicles compared to other battery chemistries, e.g., lead acid. However, a key challenge in LIB technology is the appropriate thermal management of battery cells, which is essential for ensuring battery safety, e.g., avoiding battery explosion or thermal runway events and maximizing the battery's life. The battery thermal management system (BTMS) controls individual cells' temperature, keeping them in the allowable range. This paper reviews the different kinds of BTMS, such as air, liquid, phase change material, heat pipe, and thermoelectric element cooling. In addition, hybrid systems that combine two or more cooling methods compare these technologies with power consumption methods (i.e., active or passive cooling) and state the advantages and disadvantages of each technology. Moreover, it focused on the cooling technologies considered for commercial use, i.e., if the automotive suppliers utilize them for experimental and theoretical studies. Most importantly, it identified several critical gaps that need further exploration, summarized BTMS technologies, and pinpointed directions of future work that would help researchers enhance the design of BTMS and their suitability for commercial purposes.

1. Introduction

Storage of energy in batteries for electric power vehicles (EVs), allowing for high mileage, high power, and fast charging, has been one of the most critical challenges in recent decades [1]. By improving the storage capacity and power capabilities of rechargeable Li-ion batteries (LIBs), EVs would develop faster than conventional internal combustion engine vehicles. They have become more widespread due to their zero-emission, high efficiency, and environmental friendliness. [2, 3]. EVs of today rely on LIB technology. LIB was first developed during the 1970s–1980s, and commencing with the 1990s, it was commercialized by Sony[4]. One of the important commercialization events was the partnership between the Japanese company Panasonic and the American EV company Tesla. This strategic partnership presented the world's first successful EV based on LIB technology, allowing more EV models to be developed and car makers to join this race. The global battery market for electric vehicles anticipates an exponential growth of the international light-duty electric vehicle (EV) fleet from 10 million units in 2021 to 124–199 million EVs in 2030. On the governmental level[5], many governments worldwide have started to adopt EV technology and gradually ban ICE-based vehicles [6]. Consequently, our modern transportation system will heavily rely on EV technology. With the rapid increase of EVs, the thermal management of LIB modules has become

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https://doi.org/10.21608/auber.2024.288607.1085

more crucial. Due to the high energy content stored in LIB modules, the abuse of batteries may result in explosions and fires. For example, in 2018 in California, a Tesla Model S started to smoke while parked in the street, and flames began shooting out from under it. In Canada in 2019, a Kona E.V. caught on fire while parked in a garage, and the car was not plugged in. The fire caused an explosion and damage to the structure. Also, in Florida in 2020, a Porsche Taycan was completely burned while parking in a garage [7].In Michigan in 2023, An electric Ford F-150 Lightning caught fire due to a battery issue traced back to one of the automaker's suppliers. The blaze spread to two other electric pickups in a holding lot of Fords[8]. An example of a damaged EV and its LIB module is shown in Fig.1 [9]. An efficient thermal management system for battery packs can help mitigate such accidents. Consequently, a sheer volume of research is conducted on the different possible technologies for the thermal management of battery packs. This article will review several battery thermal management technologies adopted to give the reader comprehensive knowledge. It begins by providing a background on LIB technology. Then, we discuss the thermal behavior of LIBs and briefly introduce the role of BMTS in achieving the thermal requirement of battery cells. Then, experimental and theoretical studies performed on each BTM technology will be reviewed and summarized in Tables. Finally, we provide our outlook on the remaining directions that must be considered in future studies. Among those is the development of BTMS for batteries subjected to high ambient temperatures.

1.1 Background on Li-ion batteries

Li-ion batteries offer a higher power and energy density than lead-acid, nickel-cadmium (Ni-Cd), and nickel-metal-hydride (Ni-MH). Fig.2 compares various batteries' energy densities, showing that Li-ion batteries have the highest practical energy density (90–200 Wh/kg) [2, 10]. Due to this fact, we note from Fig.3 that several car makers have adopted LIB technology for their EVs, and the energy density has kept increasing over the years. While the energy density highlighted in Fig. 3 is for the pack level, improving the energy density usually starts from the battery cell level through the advance in developing and optimizing battery materials (i.e., anode, cathode, and electrolyte) [11]. The working principle of LIBs is demonstrated in Fig.4. LIB cell is composed of a negative porous electrode (anode), a positive porous electrode (cathode), a polymeric porous separator sandwiched between the two electrodes, an electrolyte that fills up the entire porous volume of the cell, and current collectors. The anode is commonly made of carbon; graphite is commercially popular. The cathode is a lithium-containing compound typically chosen from a spinel structure, a polyanion, or a layered oxide, such as lithium cobalt oxide (LiCoO2) or lithium iron phosphate (LiFePO4). (e.g., lithium manganese oxide – $LiMn_2O_4$). Lithium salt solution in a non-aqueous solvent, such as ethylene carbonate or diethyl carbonate, serves as the electrolyte. Usually, the current collector for the negative electrode is made of copper (Cu) and a positive electrode with aluminum (Al)

Fig 1. An electric Ford F-150 Lightning caught fire [9]

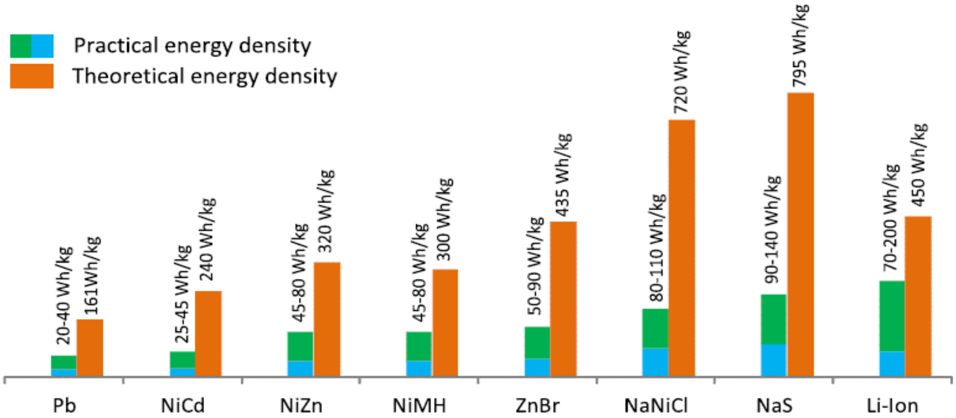


Fig.2. Various battery types' theoretical and practical energy densities [2, 10].

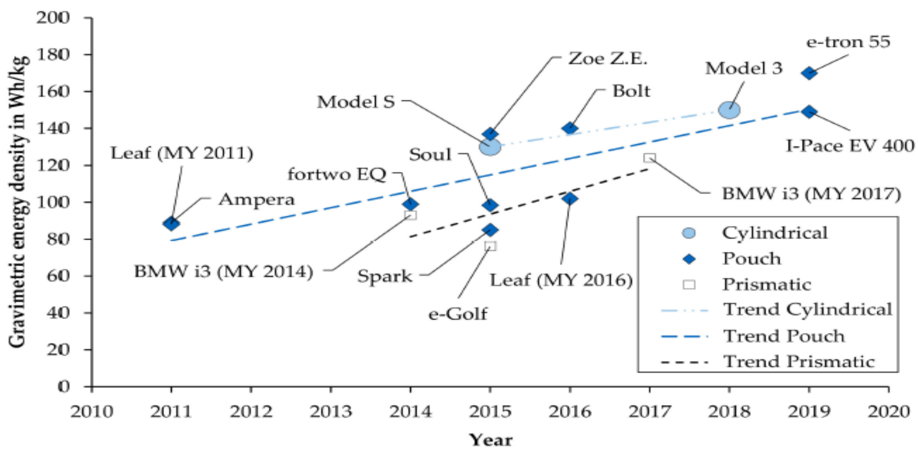


Fig .3. Energy density at the pack level for different BEVs [11].

During discharge and charge, lithium ions (Li^+) flow transversely from the anode to the cathode through the electrolyte and vice versa. [12]. The electrochemical reactions occurring at the anode and cathode, presented here for graphite and $LiMn_2O_4$, respectively, are:

$$\mathrm{Li_xC_6} \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftarrows}} \mathrm{C_6 + xLi^+ + xe^-}$$

$$\mathrm{Li_{y-x}Mn_2O_4 + xLi^+ + xe^-} \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftarrows}} \mathrm{Li_yMn_2O_4}$$

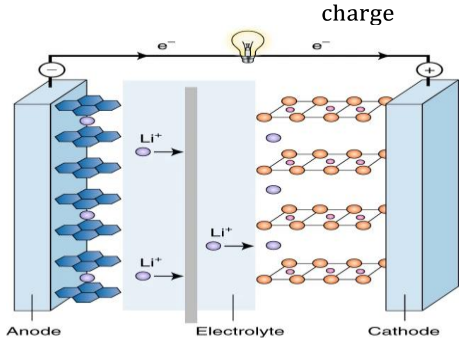


Fig. 4. A schematic shows the LIB cell's working principle [13]

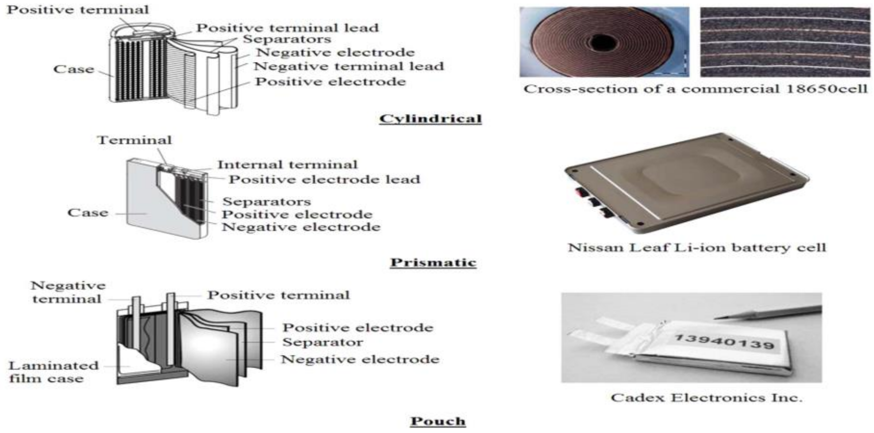
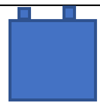


Fig.5. Battery cell type configurations [12]

The LIB cell comes in three standard formats: cylindrical, prismatic, and pouch (see Fig.5). Each structure's critical characteristics are reported in Table.1

Table 1 The difference between the properties of the three types of battery.

Cylindrical cell	Prismatic cell	Pouch cell
		
• Small size (e.g., 18650 type (ø 18 mm, H 650mm). • Hard casing. • Low individual cell capacity. • Built-in safety features. • Comparably cheap.	• Hard casing. • Large size. • High individual cell capacity.	• Soft casing. • Large size. • High individual cell capacity. • Geometrical deformation during discharging.

As shown in Fig.6, The single cells are connected in parallel and series configurations to form a battery module to achieve an electrical load's voltage and current requirements (e.g., a motor of an E.V.). The several modules can also be configured to form a battery pack (see Fig 6). As a result, the single battery pack of an EV can contain hundreds or thousands of battery cells (depending on the cell format, capacity per cell, etc.).

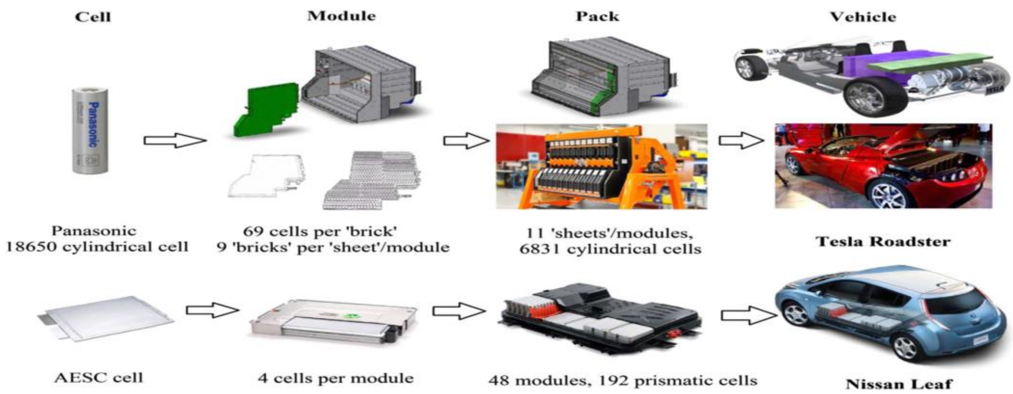


Fig. 6. Lithium-ion battery cell-, module-, and pack-level demonstrated by two-vehicle examples: Tesla Roadster and Nissan Leaf [12]

From the thermal management perspective, heat is generated in the single cell during the charging and discharging process due to the electrochemical reactions inside the cell. With the close packing of battery cells in modules and the pack, the amount of heat generated would be significant, making the existence of BTMSs inevitable. In the following two subsections, we discuss the thermal behavior of LIBs and briefly introduce BTMS.

1.2 Thermal Behavior of Lithium-ion Batteries

The temperature has a significant effect on the performance and safety of LIBs. Regarding performance, it is paramount for all cells in the battery pack not to exceed a maximum temperature limit, i.e., 45 °C. In addition, the maximum temperature difference within the single cell and between the different cells in a module should not exceed 5 °C [13]. Satisfying these strict conditions is essential to get the best performance of the batteries and prolong the battery lifetime. Regarding safety, exceeding the maximum temperature limit of the single battery cell causes a significant safety hazard and can lead to a process known as thermal runaway. Fig.7 illustrates the mechanisms of the thermal runaway process. When the battery cell is charged for the first time, some of the electrolytes react with free Li-ions near the electrode surface and form a thin film called the solid electrolyte interphase (SEI) layer [14]. This film is impervious to electrons but allows for the transport of lithium ions [15, 16]. At high temperatures, e.g., 85 °C, the SEI film decomposes and generates heat [13, 15]. If such generated heat is not removed from the battery cell, the battery self-heats at a rate greater than 0.2 °C/min, initiating the thermal runaway process. When the battery cell temperature becomes more significant than 140 °C, the second phase of the cell meltdown process is commenced, and t. The start of exothermic activity at the cathode causes oxygen to be released from the cathode to the electrolyte. The battery cell further heats up at approximately five °C/min. When the temperature reaches more than 180 °C, oxidization of the electrolyte occurs as the cathode decomposes. Self-heating rates for this phase are 11 °C/min, but they can increase to 100 °C/min. To avoid such catastrophic events, BTMS are used, as introduced in the following subsection.

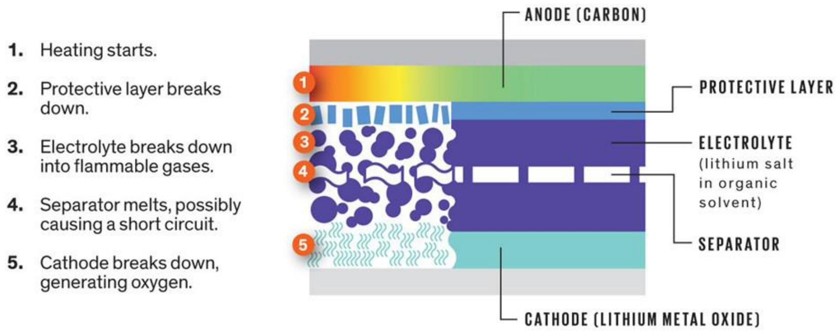


Fig. 7. Thermal runaway process concerning cell temperature [13]

2. The Battery Thermal Management Systems (BTMS)

The battery thermal management system is the mechanism that keeps the battery in a safe operating temperature range at all times, preventing thermal runaway and battery deterioration. Because BTMS is a critical part of the EV, many review papers are on the topic. Interestingly, each paper is reviewed from a different point of view. For instance, the study conducted by Shashank et al., Yasin salami et al. [17, 18], and Shankar et al. [19] focused on classifying BTMS as an active or passive system. BTMS is considered an active system if it includes power-consuming equipment like pumps and blowers. Otherwise, it is classified as a passive system. The reviews made by Yang et al. [20], Franck.[21] , Xinghui et al. [22], Pranjali et al. [23], Guodong et al. [24], Vima et al. [25], and Azri et al. [26] focused on classifying the BTMS according to the medium of cooling. Specifically, they classified the cooling technologies as air, liquid, phase change material, heat pipe, and thermoelectric element cooling. Jaewan et al. [27] classified the studies of BTMS according to the thermal cycle used in the BTMS. Specifically, they classified the BTMS into vapor compression cycles (VCC) or those without VCC. Liange He et al. [28] reviewed the research status and development trend of TMS types, control strategies, and air conditioning system refrigerants of BEVs. The above two aspects of elaboration and analysis indicate that BTMS will develop functional integration, structural modularity, control intelligence, and green efficiency. Jiling et al. [29] and Xinghui et al. [22] classified the studies of BTMS according to heating LIB at low-temperature conditions or cooling LIB at high-temperature conditions. Jiayuan et al. [2], Weixiong et al. [9], Elham et al. [30], Rezwan et al. [31], and Huaqiang et al. [32] focused their review on the numerical studies performed on BTMS. Specifically, their review discussed the thermal, electrochemical-thermal, electro-thermal, electrical equivalent models and the thermal runaway propagation models. The electrochemical-thermal models model the electrochemical processes inside the battery, including electrochemical heat generation. The thermal model gives the temperature distribution inside battery cells, and the electro-thermal models represent the batteries as equivalent electrical circuits whose circuit elements are temperature-dependent. The thermal runaway propagation models can predict thermal runaway propagation within a large-format lithium-ion battery module. Gang et al. [33] reviewed the studies of air-cooled and air-hybrid thermal management techniques. The reviews aim to provide helpful directions towards designing and enhancing air-cooled hybrid BTMS by improving the Battery pack design, Cooling channel, inlet, outlet improvement, thermally conductive material improvement, and secondary channel improvement. Omer et al. [34] review experimental and simulation studies of liquid coolant batteries. The review papers summarize the recent papers on battery liquid-cooling systems, including battery pack design, the classification of the liquid-cooling system, and coolant performance. Furthermore, it discusses factors such as the properties and applications of different liquid coolants under the types of liquid-cooling systems. Moreover, it investigates the effect of temperature on the battery's performance. Monu et al. [35], Murali et al. [36], and Ziye Lin et al. [37] review BTMS studies that use PCM as cooling with other methods of cooling. The reviews aim to study the performances of the PCM-based BTMS and the thermal properties of some PCMs whose thermal properties are suitable for use in LIBs, like the temperature of phase change, phase change enthalpy, and thermal conductivity. Dinesh et al. [38], Choudharia et al., and Wei Zhou et al. [39, 40] review the heat generation mechanism and the Thermal Behaviors and Management Systems for Supercapacitors and its effect on each battery cell component with various BTMS. Chunyu et al. [41] review the studies of BTMS, which uses a hybrid cooling system with two cooling methods. Furthermore, they compared the advantages of the hybrid system with other types of BTMS by analyzing its efficiency, cost, and other aspects.As indicated above, there are many reviews and studies on BTMs. Each review focused on some aspect. Thus, a review that combines the critical parts from all such reviews is needed. Consequently, this review will summarize the critical points and highlights of most of the past reviews and individuals studied and presented in a table format and highlight the critical advance in each BTM technology. Moreover, it identifies gaps in the literature and introduces our outlook on what needs additional focus from researchers in this important field.Consequently, this review will provide accessible, comprehensive access to new researchers in the BTM field, where they get a good summary of the past development and an introduction to potential future directions in the field. Despite such rich review articles in the literature, the scope of reviews still needs more concentration on the studies of some effective parameters. The most examples of these parameters are the economic efficiency of energy consumption, the lightweight design of BTMS, and the effect of environmental conditions on BTMS. The high ambient temperature, which needs a self-adaptive intelligent control system, should be established to improve the temperature distribution of the battery. In the following subsections, several BTMS with the advantages and disadvantages of each is discussed. In addition, a summary of the discussion is provided as a table for the reader to quickly grasp each study's essential highlights.

2.1 Air Cooling

Air cooling systems use air as the heat transfer medium. These systems can be classified as passive or active (see Fig. 8. In the passive system, the intake air could be introduced from the atmosphere or the cabin. In the active systems, the air used for battery cooling is conditioned air coming after an evaporator of the air conditioner used in the E.V. [29]. We note that both systems are forced systems, where a blower is used to introduce the air to batteries.

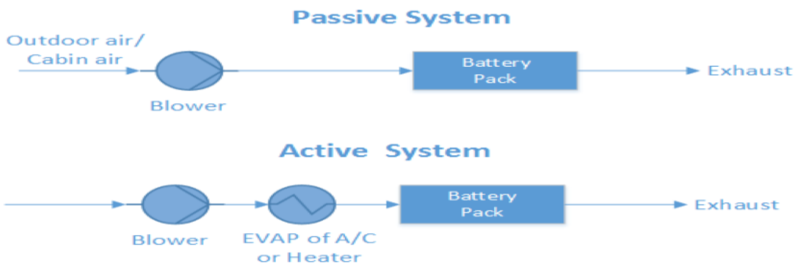


Fig. 8. Air systems (passive and active) [29]

The air-cooling system is characterized by having a simple structure and a cheap setup. On the other hand, it is limited by the low thermal conductivity of air, limited control, and high space requirements. For these reasons, air cooling is used commercially in a small energy capacity electric vehicle or low ambient temperature zones. Fig.9 shows examples of E.V.s that use air cooling, i.e., Honda Insight (left) and Toyota Highlander (right).

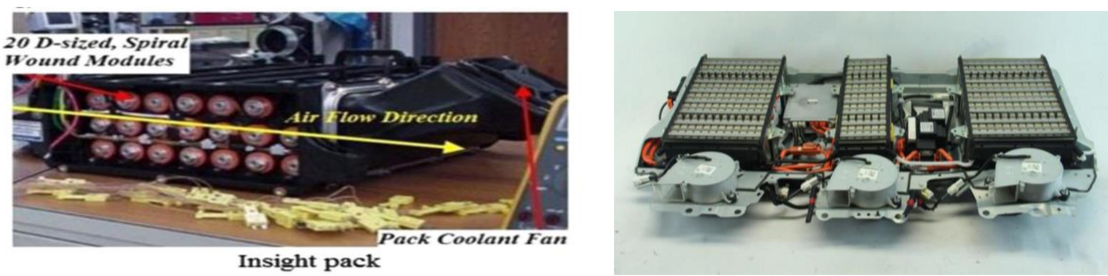


Fig. 9. Air cooling systems demonstrated by Honda Insight [8] and Toyota's Highlander [29]

2.1.1 Air Cooling Numerical and Experimental Studies

Several studies have been undertaken to develop efficient air-cooling BTMS. For instance, in 2017, Chen et al. [42] performed a structure optimization of a parallel air-cooled BTMS with U-type flow to improve cooling efficiency. They studied the influence of the operating parameters, including air flow rate, modes, patterns, and flow passage. Their numerical results show that the widths of the inlet and the outlet with a 5C discharge rate process can improve the cooling efficiency of the BTMS, reduce the temperature difference by 70% after optimization, and reduce the power consumption by 32%. Features of their design are shown in Fig.10.

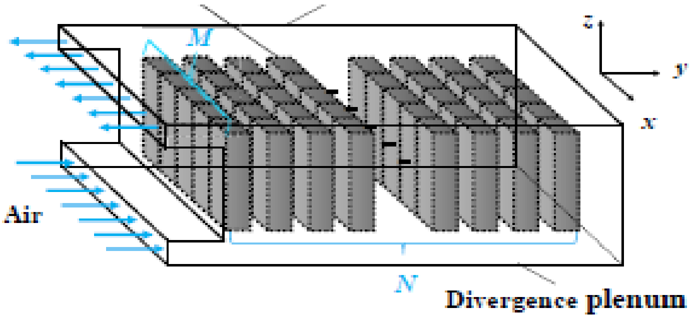


Fig. 10. Schematic parallel air-cooled BTMS with U-type flow[42]

Sihui Hong et al.[43] designed a flow configuration for a parallel air-cooled BTMS with a secondary vent (see Fig.11) . Their results showed that the position of the secondary vent strongly reduces the maximum temperature by 5 degrees or more. Compared to the BTMS without a vent, the battery cells' maximum temperature differential is decreased by 60% or more.

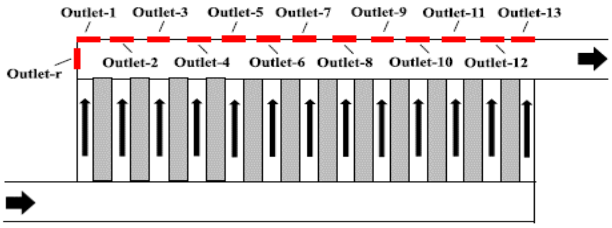


Fig. 11. Schematic parallel air-cooled BTMS with secondary vent [43]

Yuqian Fan et al.[44] experimentally studied the thermal management performance of air cooling systems (see Fig.12). Their research included the effect of studying different air inlet velocities, the discharge rate, and air inlet temperature. It was found that the temperature uniformity is improved when the air inlet temperature changes from 20°C to 30°C, and the maximum temperature difference is reduced by 12% at air velocity 0.6m/s and 20% at 1m/s when the discharge rate is 1C. Heesung et al. [45] designed an air-cooled battery system and numerically studied airflow designs to satisfy the required thermal specifications. It was found that the maximum temperatures of the battery cells directly depend on the airflow rates passing through the coolant passages. As seen in Fig.13(a), the maximum temperature is calculated to be 127 °C due to the gradual decrease in airflow rates at the coolant passages. At the same time, the expansion-shaped manifold in Fig.13(b) causes the maximum temperature to rise to 201.9 °C. In Fig.13(c), the improved airflow distribution by employing a manifold induces a lower maximum temperature of 91.2°C, which is still beyond the thermal design

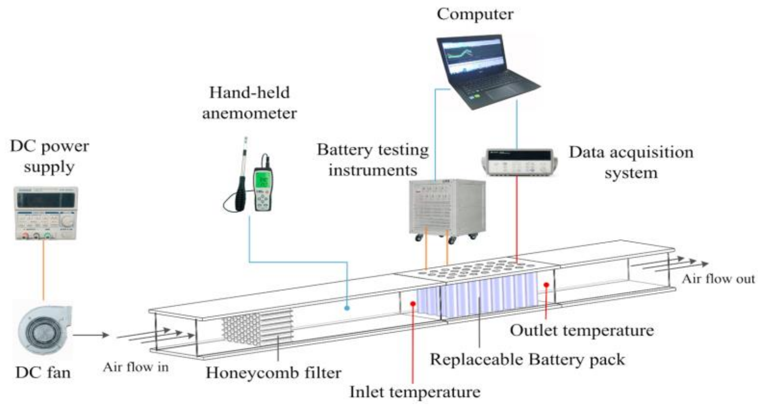


Fig.12. Schematic of the air-cooling experimental apparatus[44].

specification. As displayed in Fig.13(d), the maximum temperature of a battery cell is reduced to 61.9 °C due to the improved airflow distribution in the coolant passages than before. Finally, as displayed in Fig.13(e), the maximum temperature is 58.2°C which satisfies the thermal design specification. Thomas et al. [46] presented a mathematical model to investigate and design a BTMS (see Fig.14). The numerical method used the heat transfer model considering the horizontal position of the battery cells on the battery pack and the dynamic behavior of the battery of the electric vehicle. It was found that the increased airflow had a less significant impact on both the maximum temperature and the temperature uniformity of the model. When doubling the airflow, the maximum temperature dropped by only 0.7 ◦C compared to 1.85 ◦C in the sectioned model. Similarly, the maximum temperature difference in the battery segment is reduced by 0.2 ◦C compared to 0.85 ◦C in the proposed model.

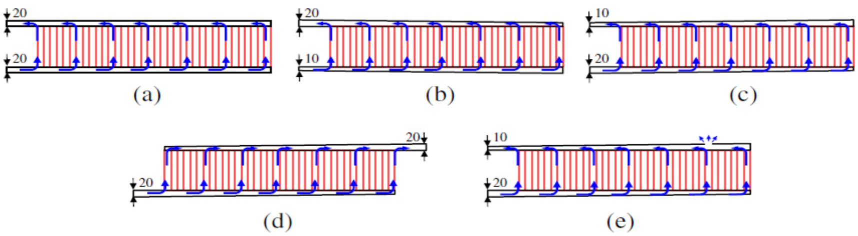


Fig. 13. Geometric configurations of the manifolds: (a) type I, (b) type II, (c) type III, (d) type IV, (e) type V; curved arrows indicate air streamlines [45].

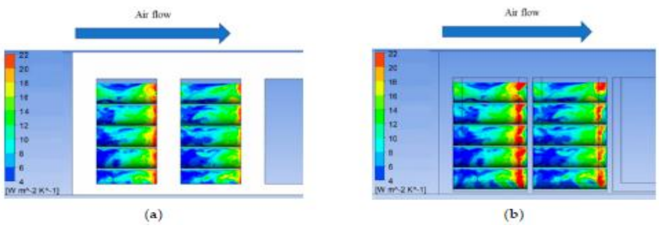


Fig 14. the heat transfer coefficient on the cells' surface (a) with visible battery segment housing and (b) with hidden battery segment housing [46].

Chanyang Kim et al. [47] Evaluated a Spoiler Model Based on Air Cooling on Lithium-Ion Battery Pack Temperature Uniformity (see Fig.15). The results show that the spoiler model reduces the maximum battery temperature by (about) 16% and effectively improves the temperature distribution of the battery cell by (nearly) 65% when compared with a conventional cooling method without a

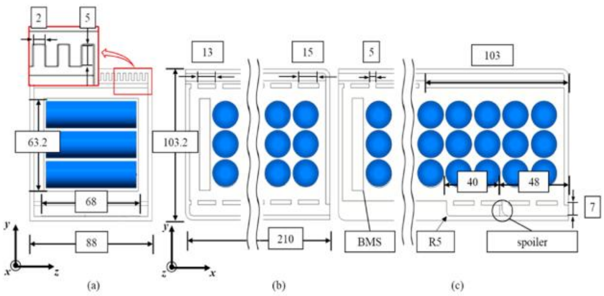


Fig 15. Configurations of the battery pack system: (a) front view; (b) top view of Z-type model; (c) top view of the spoiler-type model [47].

spoiler. Chenyang Yang et al. [48] presented Structure optimization of air cooling battery thermal management system based on lithium-ion battery two common BTMSs, the Z-type BTMS (the BTMS I) and the U-type BTMS (the BTMS II). The two structures are proposed, where the spoiler is installed at the air inlet manifold of the two initial BTMSs. By studying three structural parameters (i.e., the spoiler length L, the spoiler height H, and the offset distance of spoiler S) of two structures, two optimal BTMSs corresponding to them are obtained, respectively. Calculations were conducted at the inlet velocity of 3.5 m/s. The results demonstrate that after optimization, the maximum temperature (Tmax) and the maximum temperature difference (ΔTmax) of the BTMS III-opt are 327.43 K and 3.64 K, respectively, decreased by 2.56 K and 3.44 K (48.61%), compared with the BTMS I. Meanwhile, compared with the BTMS II, Tmax and ΔTmax of the BTMS IV-opt are 326.29 K and 1.19 K, respectively, decreased by 2.79 K and 4.98 K (80.68%).
Table 2 summarizes examples of the studied modules, including design, specification, structure pictures, and operating conditions, and reports the related thermal results.

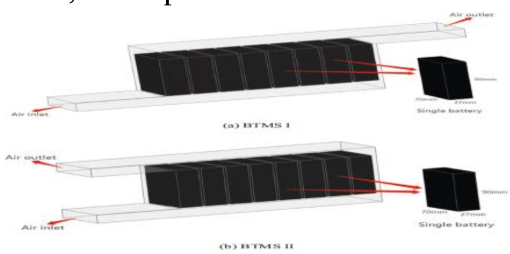
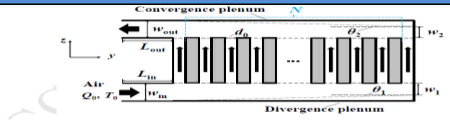
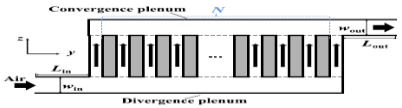
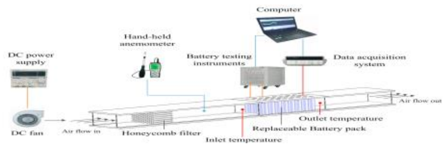
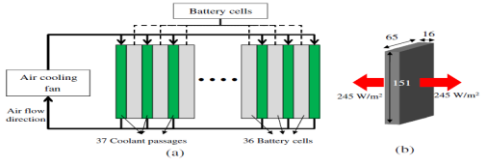
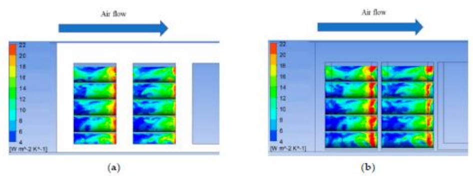


Fig. 16 Geometric model of four BTMSs [48].

2.2 Liquid Cooling

Liquid-based BTMS uses liquids, e.g., water-ethylene glycol mixture, as the heat transfer medium. Liquid cooling systems are usually classified based on the contact type between the coolant and the battery surface (direct or indirect) or the power consumption method (passive or active cooling). In direct-contact cooling, the coolant and battery cells are in direct contact, as shown in Fig.16, where a battery module is submerged in mineral water. On the other hand, indirect-contact cooling techniques employ an intermediate medium between the coolant and battery cells. For instance, discrete tubing around each module, adhering the battery modules to cooling plates, or combining the battery module with cooling fins and scales, see Fig.17. Cold plates are one of indirect cooling systems' most commonly used methods. In such a cooling method, a plate with cooling channels is inserted between battery cells, and the coolant flows through the channels of the cold plate. The advantage of this method is that it minimizes the risk associated with leakage compared to

Table 2 Summary examples of studies on air cooling in Li-ion batteries [2]

Author (Year)	Design		Module Specification		Operating condition		Important results	
	Description	Picture	Battery	cell capacity (Ah)	LIB Load c-rate	Tamb (°C)	Tmax (°C)	ΔTmax(°C)
Kai Chen [42][2017]	parallel air-cooled with U-type flow for cooling efficiency improvement		20 pouch cells	2.2	5	27	57	5.6
Sihui Hong [43] [2018]	parallel air-cooled with a secondary vent		24 pouch cells	2.2	5	27	51.85	3.7
Yuqian Fan [44][2019]	compared at different air inlet velocities: V=0.5 V=1 V=2 V=3 V=4		28 LIBs		2	25	35 28 25 23 20	21 18 17 15 12
Heesung [45][2019]	design of airflow configuration		72 LIBs	3.75	5	40	58.2	5
Thomas [46][2021]	a horizontal position of the battery cells on the battery pack		20 LIBs	3.3	3c	30	50	2.5
Chanyang Kim [49][2022]	spoiler-type model: (a) inside the model. (b) assembled battery module. (c) outside the model. (d) with the spoiler at the inlet.		27 LIBs	3.6	3c	19	28.28	2.78

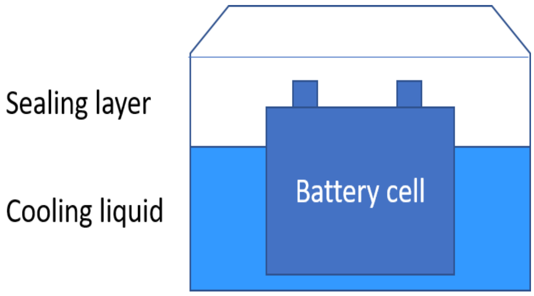


Fig. 17 Passive liquid cooling by immersing [29]

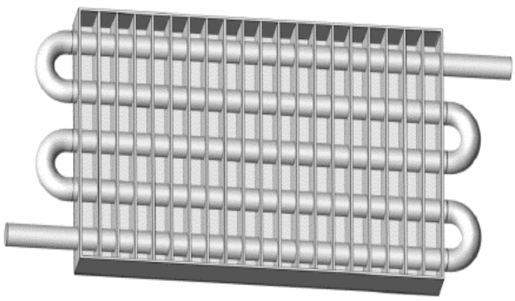


Fig. 18 Cooling fins and plates

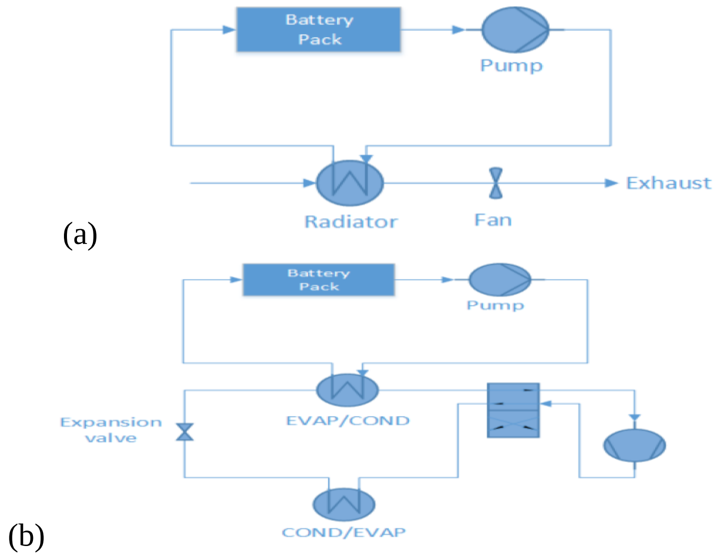


Fig. 19. Cooling circuits (a). active liquid cooling with one loop, (b) active liquid cooling with two loops [29]

direct cooling methods. Usually, liquid cooling is of the active type, i.e., it requires a pump to circulate the fluid. Fig.18 shows the two hydraulic circuits commonly associated with active liquid cooling. In panel (a), there is one loop, and a radiator is used as a heat sink for cooling; the pump circulates fluid within a closed system. As illustrated in Fig.18 (b), active liquid cooling uses two loops; the primary loop is like the loop used in the previous system, and The secondary loop is an air conditioning loop. As inferred from the previous discussion, liquid cooling has a more complicated structure than air cooling. However, the higher ability of liquid cooling to dissipate heat and achieve

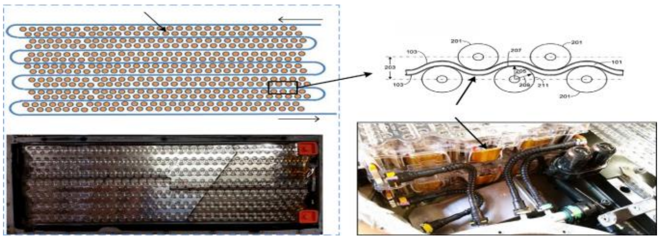


Fig .20. Liquid cooling systems demonstrated by Tesla Model S battery cooling[9]

Fig .21 Liquid cooling systems demonstrated by chevy volt [50]

higher temperature uniformity, compared to air cooling, encouraged E.V. companies to adopt liquid cooling in their E.V.s. Figs 19 and 20 show the liquid cooling system adopted by Tesla model-S, X, and Chevy Volt, respectively.

2.2.1 Liquid Cooling Numerical and Experimental Studies

Several studies have been undertaken to develop liquid and DRS cooling systems. In 2018, Tao Deng et al. [51] experimentally and numerically studied the effect of the structural parameters, including several channels on the cold plate, which had a serpentine-channel configuration. Their numerical simulation included a study of five channels and a two-channel cold plate. Interestingly (see Fig.21a,21b), the five-channel design gave the most efficient cooling performance. It could reduce the maximum temperature by 7 degrees and the temperature difference by 3.5 degrees compared with the two channels. Jiaqiang et al. [52] performed a theoretical study to analyze the influence of some parameters on the liquid-cooled battery model: width, height, velocity, and the number of channels (seen in Fig.22). An orthogonal array L16(44) is selected to design sixteen models to factors affecting the maximum temperature and temperature difference. The results show that the number of channels has the most apparent effect on the temperature of the cooling plate (maximum temperature was decreased by 5 degrees). The velocity of the coolant comes in second place (maximum temperature was reduced by 2.5 degrees). At the same time, the pipe height was found to have a minimal effect (maximum temperature was decreased by one degree).

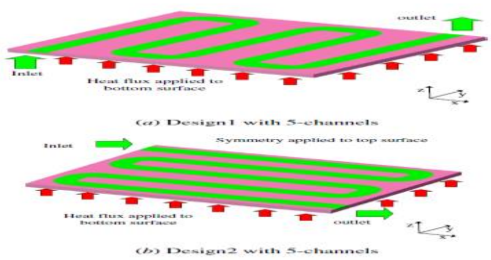


Fig. 22. The model of cold plate [51].

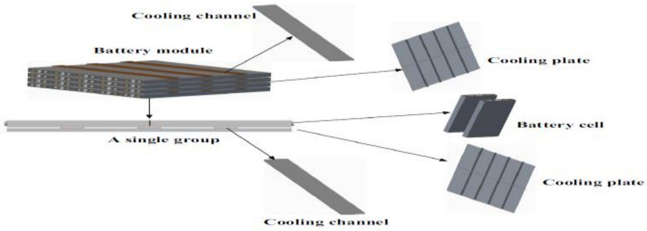


Fig. 23. Schematic of a liquid cooling battery module [52].

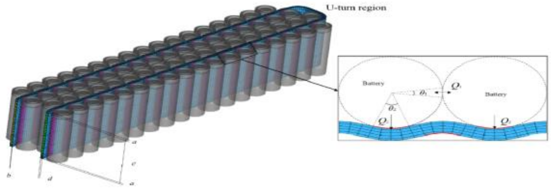


Fig. 24. Schematic of the simulated lithium-ion battery module geometry and the numerical mesh [53].

Chunrong Zhao et al. [53] experimentally studied the cooling of 71 batteries/modules by a jacket of liquid and the influence of the operating parameters, which include channel liquid flow and depth of charge (see fig.23). Their result shows that increasing the liquid flow rate conditions (e.g., the inflow velocity is 0.5 m/s and the fluid inflow temperature is 25^{o}C) can significantly control the maximum temperature below 35^{o}C and improves the temperature uniformity 1^{o}C in the battery module even when the battery module is under high C-rate (5C) discharge/charge operations. Malik et al. [54] studied the influence of using a cold plate at 10^{o}C, 20^{o}C, 30^{o}C, and 40^{o}C coolant temperatures to obtain thermal and electrical parameters for cooling a Li-ion battery pack containing three 20Ah $LiFePO_4$ prismatic cells connected in series and tested under constant current discharge rates 1C,2C, 3C and 4C, (see fig.24). The results show that the battery temperature can be kept within the required range at all four discharge rates. The discharge capacity of the battery increases with increasing coolant temperature to achieve 19.11 Ah at a one °C discharge rate with the coolant at 40°C. Huat Sawa et al. [55] designed a new system of the cooling mechanism by mist cooling for a battery module consisting of six cells arranged in a circular pattern (see fig.25) with a voltage of a single cell of 3.2 V. Therefore, the total voltage of a battery module is 19.2 V. Experimental results of bulk inlet mass flow rate with 3% mist loading fractions are found to be sufficient to maintain the maximum surface temperature of the battery below 40 °C. The battery temperature variation is less than 5°C for a 3 C-rate of charging.

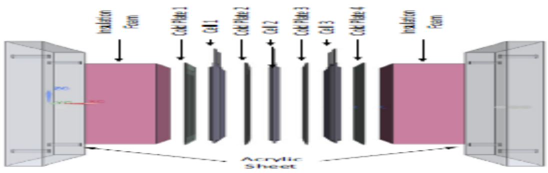


Fig. 25. Test bench for experiments expanded view of the battery pack [54].

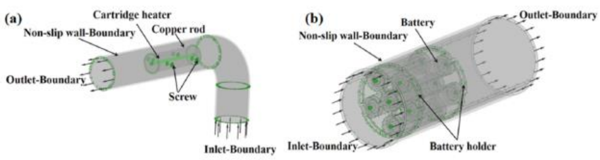


Fig. 26. (a) Boundary conditions of the test rig. (b) Boundary conditions of the battery module [55].

Siqi et al. [56] experimentally studied a liquid cooling-based cooling structure equipped with mini channels and arranged the coolant flow rates at different cooling stages(see Fig. 26). Appropriate cooling achieves the thermal objectives. It reduces energy consumption through the coolant flow rate in the cooling process under different discharging current rates, maintaining the maximum temperature of the battery module. The energy consumption of the liquid is controlled within 3.5°C and 40 J, respectively.

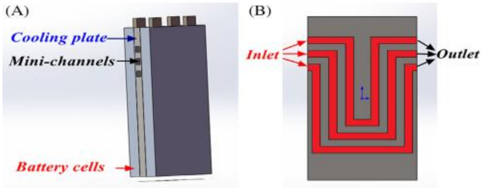


Fig.27. The cooling plate has mini channels [56].

Tao Deng et al. [57] analyzed The effects of mass flow, cold plate number, cooling direction, and channel distribution on the battery pack's thermal properties. (See Fig.27). The results showed that one g/s was suitable for heat dissipation at the mass flow of liquid. At the same time, the maximum temperatures of the battery pack were 27.67 °C and 32.17°C at discharge rates of 3C and 5C, respectively.

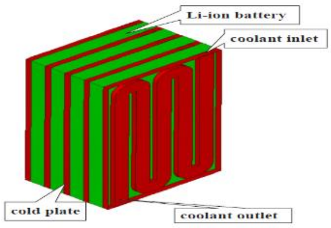


Fig. 28. The model of the battery pack [57].

Haitao et al. [58] experimentally Studied cooling by pipes inside a jacket of liquid and the influence of the operating parameters, which consider the impact of the cooling method (parallel and serial cooling) and coolant flow rate on the thermal behavior of the battery module. (see Fig 28). The findings demonstrate that lowering the temperature substantially boosted coolant flow uniformity to maximum temperature and improved the battery module in a particular flow range. Increasing the flow rate of the cooling water does not appear to improve the cooling effect when the flow rate is increased at a particular amount. Compared with serial cooling, parallel cooling can promote the temperature uniformity of the battery module. Furthermore, the designed flow direction layout can control the maximum temperature to 35.74 ℃ with a temperature different from 4.1℃

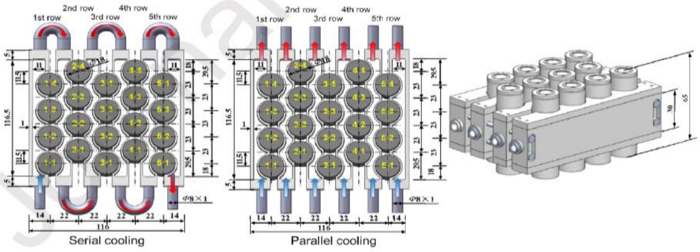


Fig. 29. Schematic diagram of the BTMS of battery module: (a) serial cooling, (b) parallel cooling [58]

Jan Bohacek et al. [59] experimentally studied a liquid-cooling system with polymeric hollow fibers (ø1 mm) embedded inside; a plastic heat exchanger is proposed for BTMS of LIB, the competitive thermal performance, and the corresponding dimensions are advantageously more minor (see Fig.29). the result showed that with the coolant inlet temperature of 20 °C and the C-rate of 1 C, the maximum temperature of the cell's during cycling was between 26 °C and 22 °C in the given range of flow rates (5–45 ml/min). Temperature spreads were 10°C and 4°C.

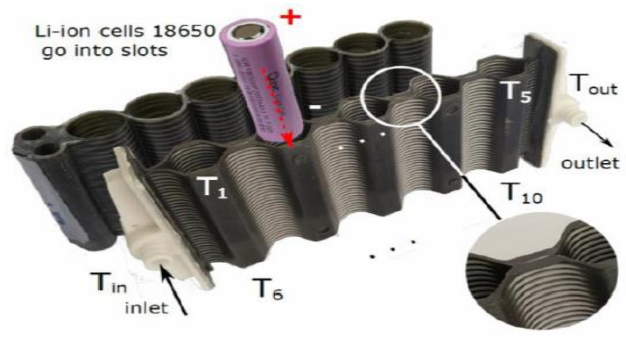


Fig. 30. A polymer heat exchanger with hollow fibers as coolant channels [59]

Table 3 Summarize the studies modules with design Figures, specifications, and operating conditions on liquid cooling in Li-ion batteries and compare the related thermal results.

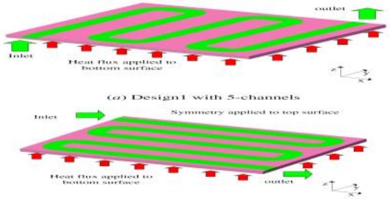
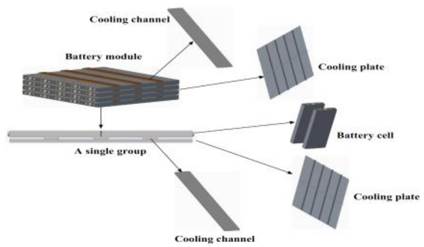
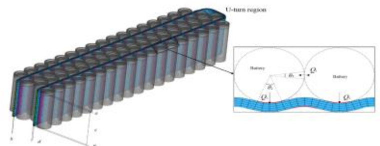
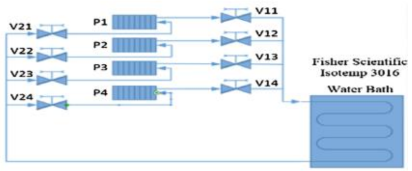
2.3 Phase change material cooling

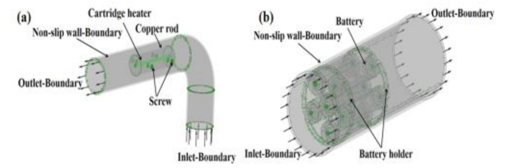
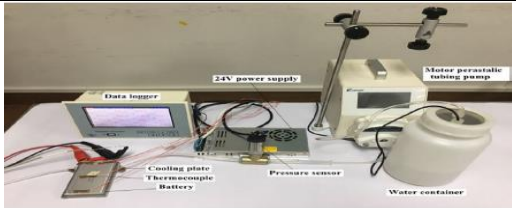
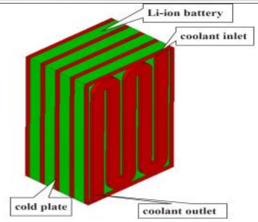
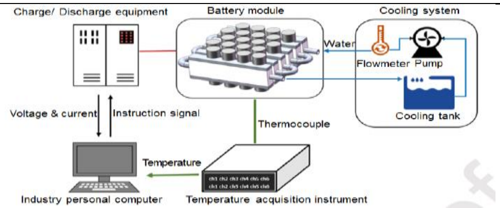
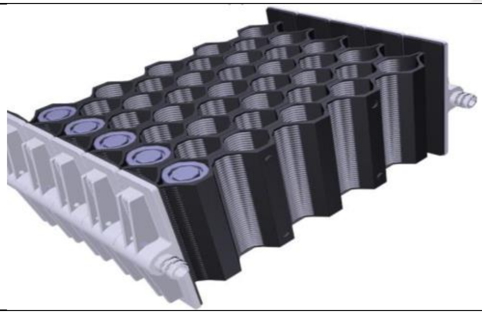
PCMs have been widely used in energy storage and cooling heat surfaces like processors and battery processes. In these materials, the phase change can be between solid and liquid phases (e.g., paraffin) or between the liquid and vapor phases (e.g., refrigerants). The working principle of PCMs, as applied in battery cooling technology, is illustrated in Fig.30. When a PCM is subjected to large amounts of heat, the PCM first experiences an increase in its temperature. Above a specific temperature, a phase-change process occurs at a constant temperature, and the absorbed heat is stored as latent heat. When a complete change of phase occurs (e.g., all solid paraffin is converted to liquid), the temperature of PCM increases. In the application of BTMS, battery cells are the heat source, and PCMs absorb the dissipated heat from the cells.

2.3.1 Liquid/Vapor PCM (Direct Refrigerants Cooling (DRC))

The direct refrigerant system uses an A/C loop for cooling, which uses refrigerant directly as heat transfer fluid circulating through the battery pack. Refrigeration cooling is the modified battery cooling system in which the selected refrigerant is a phase change material that boils to produce vapor and cools the battery packs. R134a is the commonly studied refrigerant for refrigeration cooling. The systematic layout is illustrated in Fig.31. The DRC technique mainly depends on ambient temperature, limiting its application to commercial EVs. This system needs more power consumption, as illustrated in Fig.32. Vehicle examples prefer direct refrigerant cooling, like the Mercedes S400 and AUDI A6 [60, 61]

Table 3 Summary of studies on liquid cooling in Li-ion batteries.

Author (Year)	design			Module Specification		Operating condition		Important results	
	description		Picture	Li-ion Battery	cell capacity (Ah)	Battery load (c-rate)	Tinlet (°C)	Tmax (°C)	ΔTmax (°C)
Tao Deng [51][2018]	the effect of cooling channel number on a cold plate with serpentine-channel	2- Ch 3-ch 4-ch 5-ch 6-ch		rectangular LIBs 3.2 V	10 Ah	5C	30	55 45 42 40 38	5.3 2.6 2 2 1.8
Jiaqiang [52][2018]	analyze the influence of four parameters on BTMS	Width 40 Hight 3 Velocity 0.01 channel no2 Width 55 Hight 6 Velocity 0.7 channel no5		20 rectangular LIBs 3.2 V	15Ah	3c	27	35.5 35 36.5 40 32 33 34 35	13 11.5 16 16.5 7.5 7 5 6
Chunrong Zhao [53][2018]	channel liquid flow depth of charge	0.1m/s Discharge 0.5m/s charge		(71) 18650-type LIBs	15Ah	5c	25 27	35 33	
M. Malik [54][2018]	cold plates at different coolant inlet temperatures and current rate	10c 20c 30c 40c		(3) series 20Ah LiFePO4 prismatic cells	20Ah	4c	40	38.7 39.2 39.5 40.7	

Huat Sawa [55][2018]	mist cooling bulk inlet mass flow rate with 3% mist loading fractions	 Fig. 3. (a) Boundary conditions of the test rig. (b) Boundary conditions of the battery module.	(6) LIBs phosphate batteries	3.2 Ah	3c	30	40	5
Siqi Chen [56][2019]	experimental investigation liquid cooling with mini channels cold plate and arrange the coolant flow rates		LIBs soft-pack battery cell	8-Ah	0.5c 1c 1.5c	25	26 32 40	3.5
Tao Deng [57][2019]	analyzed the effects of mass flow, cold plate number, channel distribution, and cooling direction		(4) series 20Ah LiFePO4 prismatic cells	10Ah	3c 5c	25	27.67 31.96	2.64 7.10
Haitao Wang [58][2020]	The 3D model of the battery module was established and meshed by using ANSYS software package		(20) 18650-type LIBs	2.2 Ah	3c	30	35.74	4.17
Jan Bohacek [59][2022]	A plastic heat exchanger was introduced to be used in battery modules of electric vehicles.		(25) 18650-type LIBs	2.2Ah	1C	20	26	4

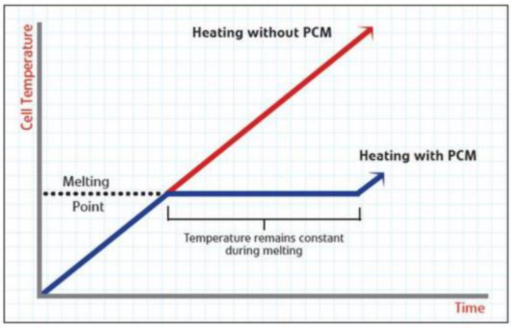


Fig.31. the working of PCM on battery cells [29]

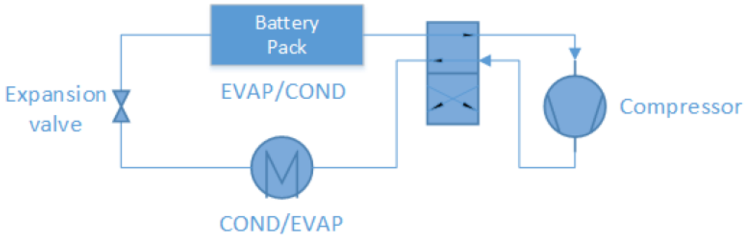


Fig.32. direct refrigerant system [29]

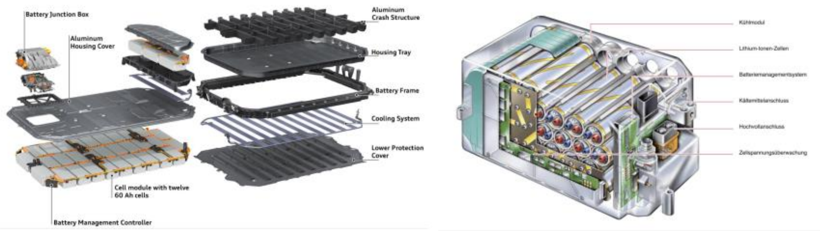


Fig. 33. Two-vehicle examples demonstrate DRS cooling systems: Audi and Mercedes s400 [60, 61]

2.3.2 Direct Refrigerants Cooling Experimental and Simulation Studies

DRS cooling has become the new research interest for cooling lithium-ion batteries. In 2017, Maan Al-Zareer et al. [62] presented research on refrigeration-based BTMS by varying the refrigerant and battery pack arrangements and developing a three-dimensional electrochemical thermal model. In the proposed system, the batteries are submerged partially in saturated liquid propane that cools the battery by absorbing the thermal energy generated by the battery. This phenomenon causes boiling, producing a vapor that cools the remaining part of the battery (See Fig.33). The result showed that when the propane covers the battery length, 30% keeps the temperature below 34^{o}C.

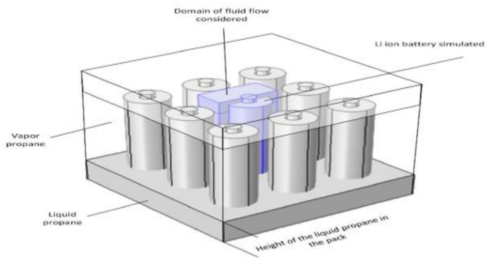


Fig. 34. Schematic diagram of the battery thermal management system[62].

Maan Al-Zareer [63] et al. studied a model's performance of ammonia boiling-based BTMS. Ammonia-based hybrid electric vehicles are within the optimum operating range (see Fig.34). The system is simulated for a 4C discharging and charging cycle for 600 s. The proposed method results are promising, as it can maintain the maximum temperature of the battery below 33ºC when only 5% of the front battery surface is covered with a boiling ammonia pool.

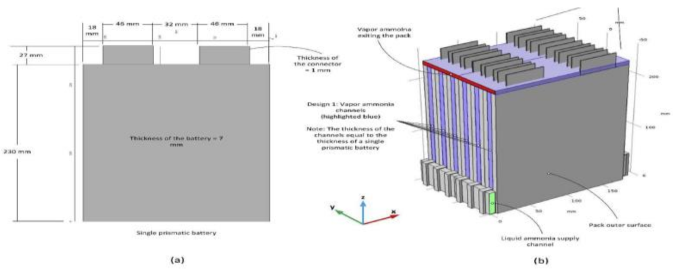


Fig. 35. Schematic of (a) dimensions of the prismatic battery, (b) the battery pack integrated with the proposed ammonia-based cooling system [63]

Seong Ho Hong et al. [64] presented a study of a novel direct two-phase cooling using R-134 refrigerant over a conventional liquid cooling (see Fig.35). The two-phase refrigerant cooling satisfies the maximum cell temperature limit of 45 °C even under harsh environmental conditions.

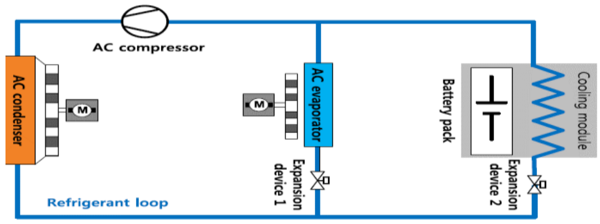


Fig. 36. Schematics of direct two-phase refrigerant cooling [64].

2.3.3 Solid / Liquid PCM

Three main PCM types are commonly used for Solid / Liquid PCM, which are organic, inorganic, and eutectic materials. Particular attention is paid to the thermophysical properties of these materials, i.e., density, thermal conductivity, specific heat, and latent heat. For instance, matching the melting point of PCMs and the allowable maximum cell temperature is an important consideration. A PCM with a melting temperature below 45°C and a desirable maximum temperature below 50°C is preferred to provide efficient heat dissipation and better temperature uniformity among battery cells. [65].Typically, PCM has poor heat conductivity. Therefore, additives can be used to increase thermal conductivity. PCM should have a high latent heat per unit mass and thermal cycle life, low density, be safe and chemically stable, and be non-toxic and inert to other battery components. Table 10 shows the most suitable PCM properties with appropriate additives; PCM is always combined with different cooling methods like air or liquid cooling systems to enhance the battery temperature[35].

2.3.4 Solid / Liquid PCM Cooling Simulation and Experimental Studies.

Several studies have been undertaken to develop PCM cooling (BTMS) systems for an instant. In 2008, Kizilel et al. [67] numerically Studied using PCM at a high ambient temperature of 45 ◦C and discharge rate of 2.08C-rate (10 A). The PCM (Graphite matrix) was drilled with holes of 18.2 mm diameter. LIB cells with 2.4Ah capacities were placed(see Fig.36). The results showed that the temperature difference along the pack with PCM was only 4 ◦C, and the pack with PCM was kept below 45 ◦C at all times, which is preferred for Li-ion cells.

Table 4 shows the most suitable PCM properties with appropriate additives [66].

PCM/thermal conductivity (W/m K)	**Paraffin/0.2**	**RT-42 paraffin/0.2**	**Inorganic eutectic/0.47**
Melting point (°C)	23	43	39-45
Density (solid) (kg/m3)	900	910	1420-1470
Density (liquid)(kg/m3)	760	765	1442-1670
Specific heat (solid) (kJ/kg K)	2.1	2.1	1.1- 2.1
Additives thermal conductivity (W/m K)	Graphite	Expanded graphite/ 4–100	Carbon fiber 175–200
Composites thermal conductivity (W/m K)	70	16.6	0.45-1.8
Ratio of composite (%Wt)	35	26.6	8-12
Latent heat of PCM without/with additives (kJ/kg)	136/179	185/250	180/195

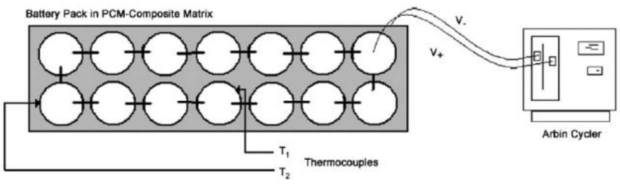


Fig. 37. Schematic of the experimental setup (not scaled) [67].

Sijie Zhang et al. [68] studied the inorganic sodium polyacrylate hydrogel (PAAS) as PCM in BTM (see Fig.37). This material is usually used in the medical field. Their results for 4S1P and 5S1P battery modules proved the effectiveness of using this hydrogel BTMS in lowering the temperature under 36°C and the temperature difference during operation under 6°C.

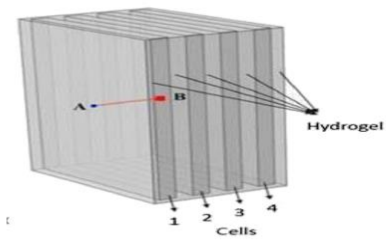


Fig. 38. Schematic illustration of the model battery pack with hydrogel TMS [68]

Charles et al. [69] experimentally studied the paraffin wax for cooling the li-ion battery (see Fig.38). The results showed that the PCM battery management system improves the temperature uniformity during its melting, i.e., the temperature difference was limited to 1.8 °C. In addition, the maximum temperature did not exceed 28°C.

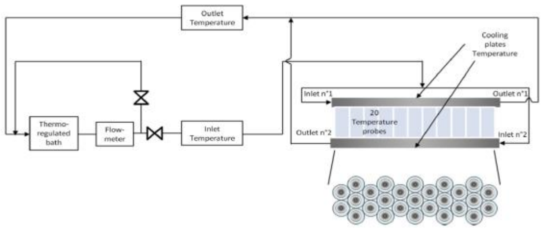


Fig. 39. Experimental setup of the semi-passive BTMS [69].

Z.G. Qu et al. [70] Experimentally Studied adding paraffine wax with copper foam. Fig.39, the batteries connected in series were fixed in a glass cage. Each N-type thermocouple was glued to the center of each battery. The surface temperature of the battery was measured at a discharge rate of 1C in isothermal mode. The initial discharge temperature was 28.5 C, and data were tracked every 30 s. The result showed that the structure improves the strength of the PCM during its melting with a maximum temperature under 58°C.

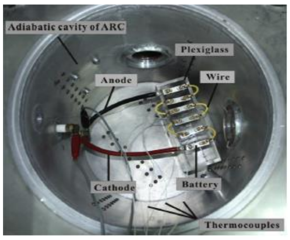


Fig. 40 Surface temperature of the battery at 1C discharge tested by ARC in adiabatic mode [70].

Rui Zhao et al. [71] Optimized a phase change material (PCM) based BTMS was proposed by replacing the hollow mandrel in a cylindrical battery with a PCM-filled mandrel tested on a fabricated steel cell. (See Fig.40) The numerical results showed that the PCM cores could effectively alleviate the temperature rise inside the battery pack and uniform temperature distribution as the PCM core radius increases to 3.8 mm. The peak temperature of the battery module can be managed below 50 °C, and the maximum temperature difference can be maintained within 2°C under natural convection.

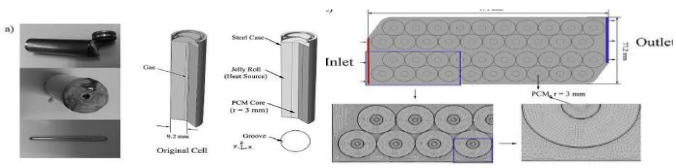


Fig. 41. a) Illustrations of the internal structure of a disassembled 18650 cylindrical battery b) Schematic of a hybrid cooling design for the battery pack[71].

Ping Ping et al. [72] experimentally Studied PCM cooled modules with fin structure (see Fig .41). The results showed that PCM with fin structure BTMS design enhanced the thermal performance and kept the battery's maximum temperature at less than 51°C at a relatively high discharge rate of 3C. Yantong et al. [73] Experimentally Studied composite phase change materials (C-PCMs) paraffine wax with expanded graphite (EX) used to improve the properties of cooling. The radiuses of the PCM unit in different conditions are identified (R=48,50,15,52mm) (see Fig.42). The results indicate that the proposed optimization method is effective, the system kept of maximum temperature under 70°C and temperature different under 3.4°C.

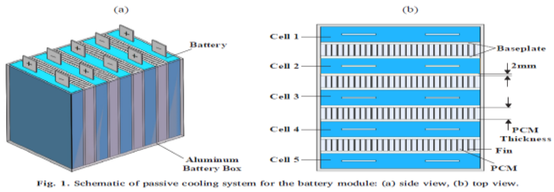


Fig. 42. Schematic of passive cooling system for the battery module: (a) side view, (b) top view [72].

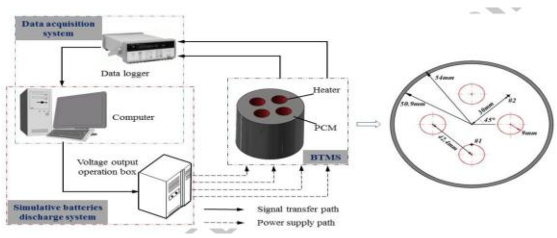


Fig. 43. The schematic diagram of the test rig for the BTMS with PCM [73].

R. Ziyuan et al. [74], Xiaoming et al. [75], and Fereshteh et al. [76] studied adding paraffine wax with carbon fiber to improve the properties of cooling(see Fig.43). The results showed that the PCM thermal conductivity was enhanced by adding carbon fiber and the development of maximum temperatures under 55°C,48°C, and 57.2°C, respectively.

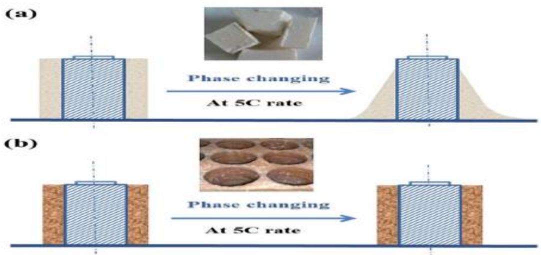


Fig. 44. (a) the battery with pure paraffin and (b) the battery with CF/PCM [74].

Deqiu et al. [77] studied C-PCM Paraffin wax using graphene and carbon nanotubes (see Fig.44). The results showed that the composite PCM at the multi-walled carbon nanotube carbon nanotubes (MWCNT)/ graphene mass ratio of 3/7 could enhancement heat transfer effect. The thermal conductivity was increased by 124% compared to graphene PCM, resulting in a maximum temperature under 55°C. Table.5 Summarize the study modules with design Figures, specifications, and operating conditions using PCM cooling Li-ion batteries.

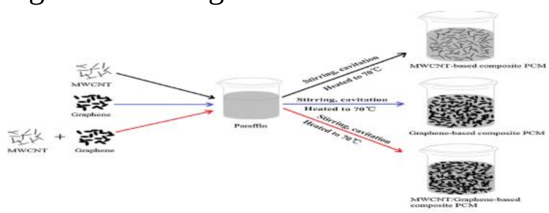


Fig. 45. Preparation process of composite PCM [77].

Table 5 Summary of Studies on Direct Refrigerant Cooling in Li-ion Batteries.

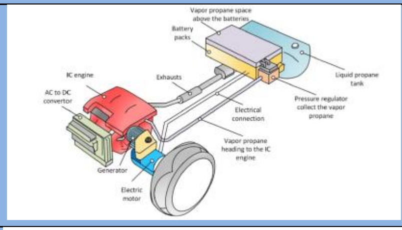
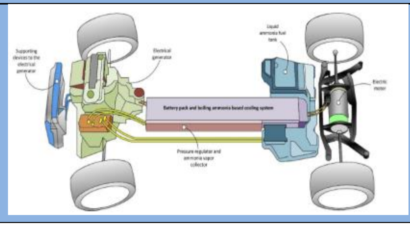
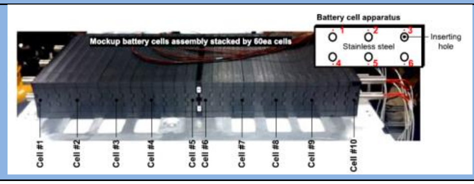
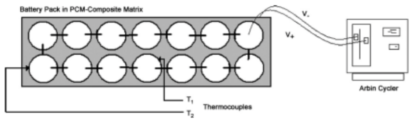
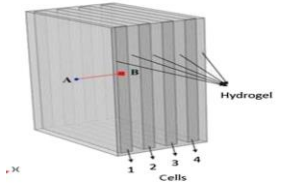
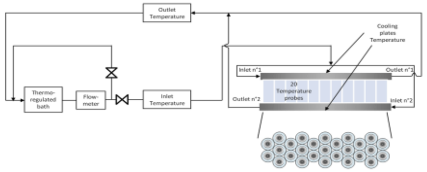
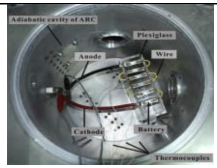
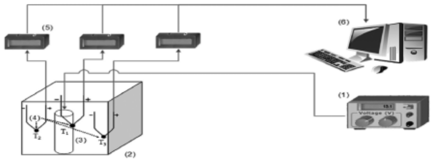
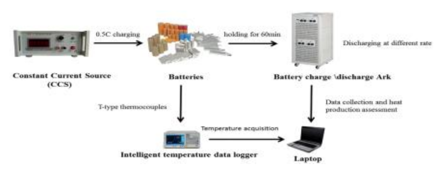
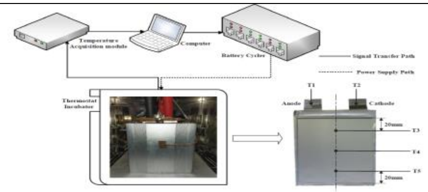
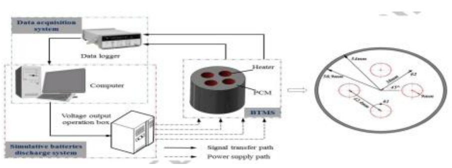
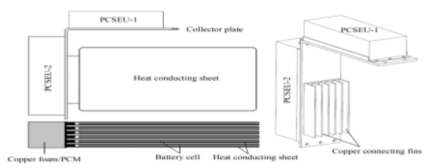
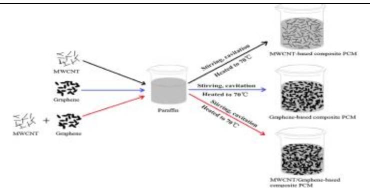
Author (year)	Design		Description	Operating condition		Important Result
	Refrigerant TYPE	Picture	Battery capacity	battery load (c-rate)	Tamb (°C)	Tmax (°C)
Maan Al-Zareer [62] [2017]	Proban		10Ah 10 prismatic cells	7.5C.	25	34
Maan Al-Zareer [63] [2018]	Ammonia			4c	25	35
Seong Ho Hong[64] [2020]	R-134			2c	25	45

Table 6 Summary of studies on solid/liquid PCM cooling in Li-ion batteries.

Author (year)	Design		description		Operating condition		Important results	
	PCM TYPE	Picture	Battery capacity	Melting point	battery load (c-rate)	Tamb (°C)	Tmax (°C)	ΔTmax (°C)
Kizilela [67][2008]	PCM at high current and ambient temperature		10Ah	42–45C	2.08c	45	80	
Sijie Zhang [68][2014]	water based PAAS (sodium polyacrylate) hydrogel BTMS		4S1P 3 Ah		10A	30	36	6
Charles [69][2014]	paraffin wax (Rubitherm RT28 HC)		26 heaters 300 V 2.8 A	43-45c	3c	26	28	1.8
Z.G. Qu [70][2014]	composite paraffin with copper foam		square LIBs (3.8 V, 10 Ah)	42-49.	3c	30	58	-
Fereshteh [76][2016]	composite paraffin wax with carbon fibers: Blank % 0.32 %0.46 %0.56 %0.69		14.5Ah	42-49	2w	22	57.2 57 56.8 56.4	

Ziyuan Wang [74][2017]	composite paraffin with copper foam	-without paraffine -with copper foam		10 Ah	45-47c	5c	35	55 45	
Rui Zhao [71][2017]	Replacing the hollow mandrel in a cylindrical battery with a PCM-filled mandrel,			2.6Ah	27-44	1.92c	24	50	2
Ping Ping [72][2018]	paraffin wax with a fin structure	w/out fins 2 mm 1.5mm 1 mm 0.5mm		10Ah Five prismatic cells	43c	3c	40	53 52 51 50	5.2 5.2 4.8 4.7
Yantong Li [73] [2018]	composite paraffin with expanded graphite with different radius	R=48 R=50 R=51 R=52		4 electrical heaters	44c	3 c 2.8c 2.5c 2.4c	25	70 65 62 58	3.4
Xiaoming [75] [2019]	paraffin with copper foamed	-PCSEU-2 (case1) -PCSEU-2 (case2) -PCSEU-1 (case3) -PCSEU-1 (case4)		10Ah	35-38c	5 c 4c 3c 2c	34	48 48 36 34	6
Deqiu Zou [77][2018]	Paraffin wax using graphene and carbon nanotubes	Paraffin 0.7%graphene +0.3%(CNT) 0.2%graphene +0.8%(CNT)			44	2c	15	55 45 42	

2.4 Heat Pipe Cooling

The heat pipe (H.P.) has been widely used for thermal cooling in many fields in recent decades, such as solar energy collectors, central processing units (CPUs), micro projectors, laser generators, and spacecraft [78]. An HP is a two-phase heat transfer component and consists of three segments: evaporator, condenser, and adiabatic section. The heat is transferred from the evaporator to the condenser. A BTMS integrated with H.P. is a cooling solution for heat control of LIBs in E.V.s. As illustrated in Fig.45, the heat pipe is an envelope under a partial vacuum. The capillary structure is made of sintered copper powder. Working fluid on the evaporator side will absorb heat and become vapor lower than 100°C due to low pressure; on the condenser, vapor will dissipate heat to the surroundings and become liquid again. In a typical HP-based BTMS, the evaporator is attached to the battery surface to reduce heat transfer resistance.

In contrast, the condenser is coupled with cooling media to enhance heat dissipation[79]. As illustrated in Fig.46 and according to their working principles, H.P. can be categorized as the flat heat pipe (FHP), tubular heat pipe (THP), oscillating heat pipe (OHP or PHP), or loop heat pipe (LHP). Choosing the working fluids is dependent on the operating temperature of heat pipes. According to the working temperature of LIB, potential functional fluids for HP-based BTMSs are between 20°C -140°C. Other factors, such as latent heat, specific heat, and capacity surface tension, should also be considered when choosing an adequate working fluid. The advantages include lightweight, high heat transfer efficiency, flexibility, easy installation, and low cost [80].

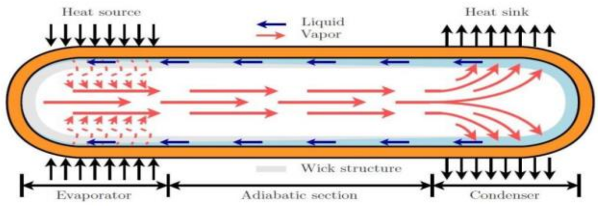


Fig. 46. Structure of the heat pipe [13]

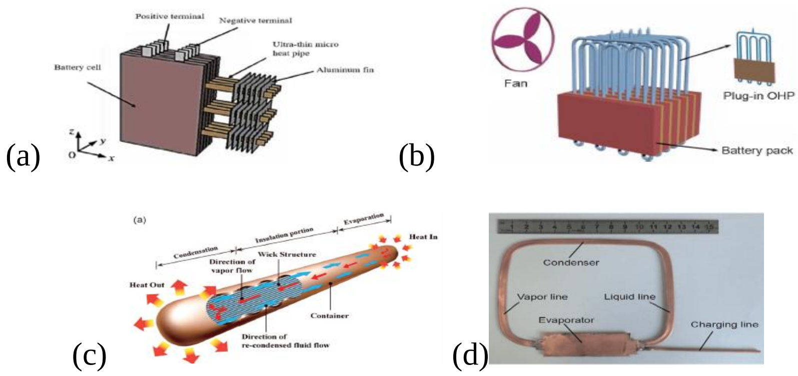


Fig.47 (a) FHP (b) OHP (C) THP (d) LHP [79]

2.4.1 Heat Pipe Cooling Simulation and Experimental Studies.

Heat Pipe cooled LIBs are usually combined with other types of cooling in BTMSs.For example, Rui Zhao et al. [81] experimentally studied heat pipe BTMS with the wet cooling method for LIBs to enhance the cooling temperature during high-rate operations. The BTMS used a thin heat pipe to transfer the heat from the battery to the cooling ends, where the evaporation process can rapidly

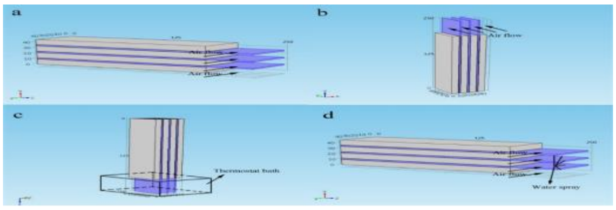


Fig. 48 . Schematic illustrations of four BTM systems: a) horizontal heat pipes with cooling fan, b) vertical heat pipes with cooling fan, c) heat pipes in a thermostat water bath, and d)horizontal heat pipes with a wet cooling system [81].

dissipate the heat (see Fig.47). The result showed that the cooling integrated HP BTMS was effective in cooling through series tests. With a 3 Ah battery pack, the maximum temperature elevations during all C-rate discharges are below 4°C. The temperature difference is below 1.5 C.Z.Y. Jiang et al. [82] numerically studied heat pipe coupled with phase change material during discharge–charge cycle for cooling(see Fig.48). The numerical and experimental results in the discharge process are monitored. The maximum temperature deviation is 0.8 °C.

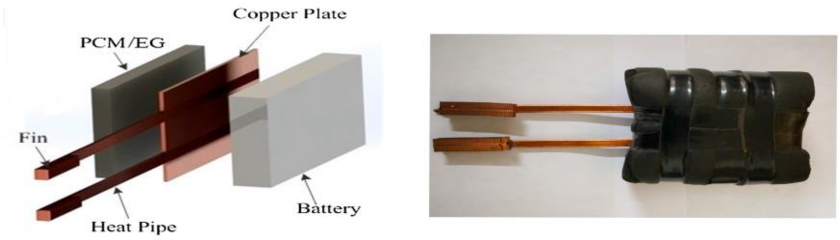


Fig. 49. Schematic of the thermal management module [82].

Wangyu Liu et al. [83] Experimentally investigated the thermal management of cylindrical Li-ion battery packs based on a vapor chamber combined with a fin structure (see Fig.49). The results show that the vapor chamber can decrease the temperature rise and improve the uniformity of temperature distribution within the battery pack. The result showed a complete discharging at the maximum temperatures of 43.89 °C, 52.75 °C, and 66.34 °C at the discharge rates of 2°C,3°C, and 5°C, respectively. The temperature difference after completely discharging is 5.3 °C, 6.8 °C, 8.5 °C at the discharge rates of 2°C, 3°C, and 5°C, respectively. After cooling the maximum temperatures reduced by 7.79 °C, 11.16 °C, and 16.21 °C, the temperature differences reduced by 3.7 °C, 4.1 °C, and 3.2 °C at the discharge rates of 2°C, 3°C, and 5°C, respectively.

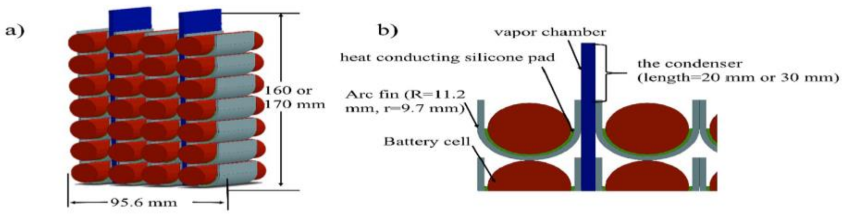


Fig. 50. The vapor chamber BTM system demonstration: (a) structure size for the BTM system; (b) constituent elements for the BTM system[83].

Tang Wei et al. [84] studied research done on BTMS's Sensitivity Analysis with a Reciprocating Cooling Technique and a Flat Heat Pipe. To reduce the battery module's temperature uniformity (see

Fig.50). The outcome shows that the reciprocating cooling technique may enhance the BTMS's temperature performance. The heat transfer performance of the flat H.P. could transfer the heat of the battery cells to the liquid, resulting in a maximum temperature rise under s 3.46 °C and a temperature difference of 2°C.

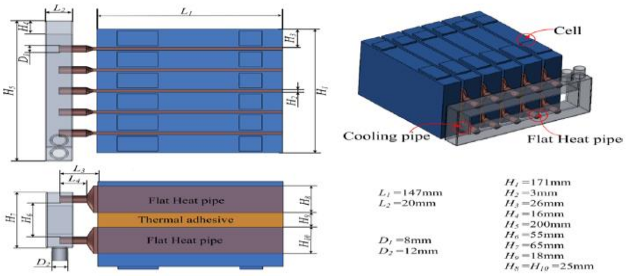


Fig 51. Relative position relationship and dimension parameters of each model component [84].

Nan Mei et al. [85] also analyzed the Heat Dissipation on the Flat Heat Pipe Coupled with a Liquid Cooling System of a Lithium-Ion Battery (see Fig.51). It showed the effectiveness of balanced performance. Even if the maximum temperature difference inside the power battery system is significant, the uniformity of the temperature distribution of the power battery system is still good—the result of a maximum temperature under 32 °C and a temperature difference of 5.8°C. Table.7 Summarize the studies modules with design Figures, specifications, and operating conditions using heat pipe for cooling in Li-ion batteries.

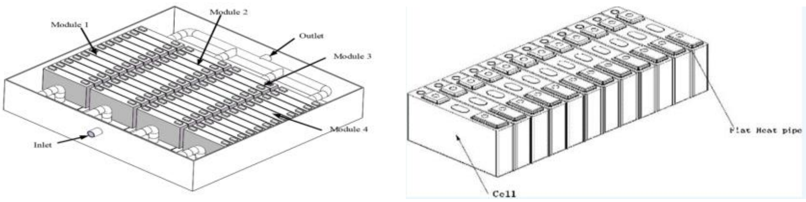


Fig .52. Lithium-ion battery system 3D model [85].

Hamidreza Behi et al . [86] experimentally studied a heat pipe sandwiched configuration cooling system (SHCS) combined with air cooling with a value of 8c current discharging rate (see Fig.52). The results indicate that the maximum temperature in natural convection reaches 56.8 °C. Forced convection for the cell under 37.8 °C reduces the cell temperature compared with natural air cooling by up to 33.4%.

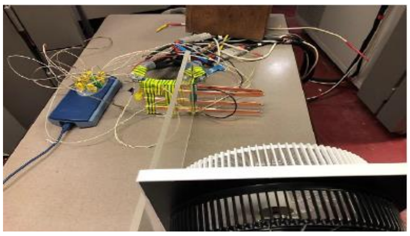
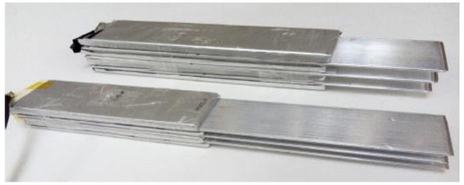
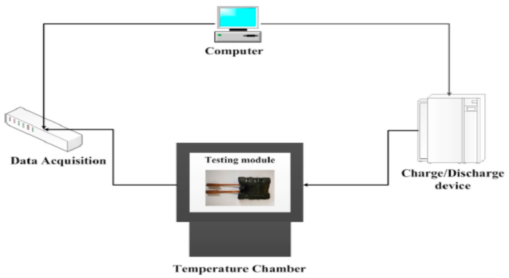
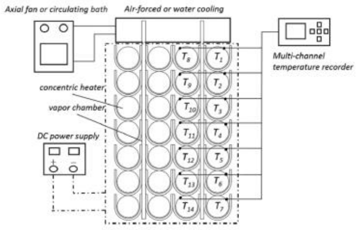
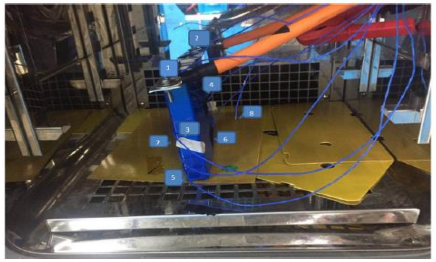
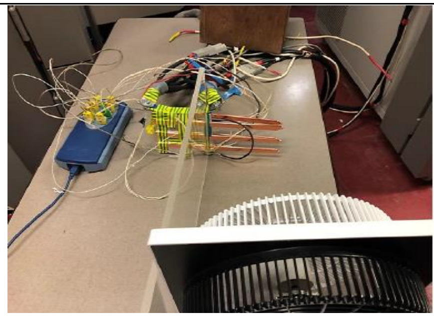


Fig. 53. The battery cell embedded with SHCS in the presence of forced convection and natural convection [86]

Table 7 Summary of studies on heat pipe cooling in Li-ion batteries.

Author (Year)	Design			Battery Description		Operating condition		Important results	
	description		Picture	type	capacity (Ah)	Load c-rate	Tamb (°C)	Tmax (°C)	ΔTmax (°C)
Rui Zhao [81][2015]	heat pipe with wet cooling	Ambient HP HP, fan H.P., bath H.P., wet		Four prismatic batteries in series (4S1P)	8Ah	2c	25	38 36 32 20	2.5 2 1.8 1
Z.Y. Jiang [82][2019]	heat pipe and phase change material			Prismatic LIB	8Ah	1c	40	48	
Wangyu [83][2019]	vapor chamber combined with a fin structure		Fig. 2. Schematic of the experimental set-up.	(28) 18650-type LIBs	20Ah	2c 3c 5c	25	36.1 41.15 50.13	1.6 2.7 5.3

Tang Wei [84][2020]	Flat Heat Pipe in Combination with a Reciprocating Cooling Method Reciprocating Cooling Strategy Combined with a Flat Heat Pipe			Prismatic battery	60Ah	2c	20	23.7	2
Nan Mei [85][2020]	Liquid Cooling with a Flat Heat Pipe	700 l/h 750 l/h 800 l/h		Square-Shell Ternary Lithium-Ion Battery	38Ah	3c	20	32 30	5.8 4.6
Hamidreza [86][2022]	Flat Heat pipe with air-cooled system			Prismatic LIB	8Ah	8c	22	37	

2.5 Thermo-Electric Module Cooling (TEC)

As shown in Fig.53, the Thermoelectric cooling was mainly composed of a series of P-type and N-type thermoelements, the elements connected using a metal conductor [87]. TEC forms cold and hot sides as the current passes through the unit and the energy transfers through the circuit [16]. The outside is attached to the battery and needs to be cooled. The hot side is connected to the dissipating device, as illustrated in Fig.54. The TEC cooling system is always combined with other types of cooling like PCM, liquid, and H.P. cooling.

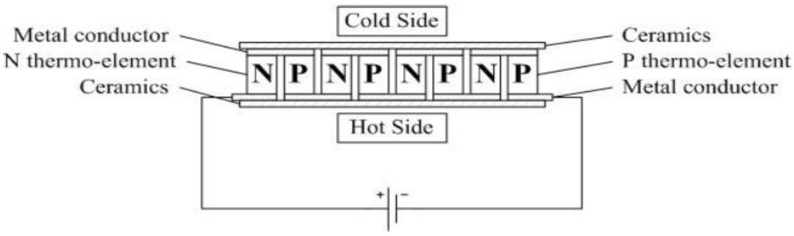


Fig.54. The thermoelectric cooling (TEC) structure.

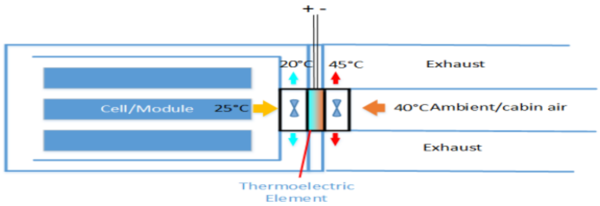


Fig.55. thermoelectric cooling/heating system [29]

2.5.1 Thermo-Electric Module Simulation and Experimental Studies

Studies have been undertaken to develop Thermo-electric Module systems. Like H.P. cooling, TEC-cooled LIBs are usually combined with other types of cooling in BTMSs. In 2018, Chuan-Wei Zhang et al. [88] Studied the BTMS Based on a Thermoelectric Effect. The liquid cooling unit contains a thermoelectric chip. It is designed for a battery cell. The effects of inlet velocity on the heat exchanger were studied (see Fig.55). The results showed that the U loop structure is more reasonable. When the inlet velocity is 1.0 m/s, the flow field distribution is uniform, and the maximum temperature of the battery could be lowered to 18°C because of the integrated thermoelectric cooling system's more even temperature distribution.

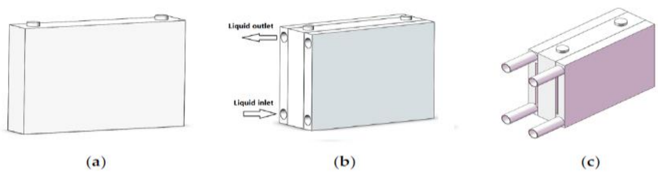


Fig 56. Three- models. Models with a single battery, water, and thermoelectric cooling [88].

Chuan et al. [89] Study of BTMS Using Composite Phase Change Materials and a Thermoelectric Cooling Sheet for a Power Battery Pack (see Fig.56). the result found that combining CPCM with semiconductor refrigeration technology can control the maximum temperature of the battery surface within 45°C, and the temperature difference is contained within 4°C. You Lyu et al. [90] experimentally enhanced BTMS with thermoelectric cooling. The BTMS is a combination of forced air cooling, thermoelectric cooling, and liquid cooling. (See Fig.57). The experiment showed that the battery surface temperature drops from 43°C to 12°C when 12 V is supplied to the TEC and 40°C to the heater module.

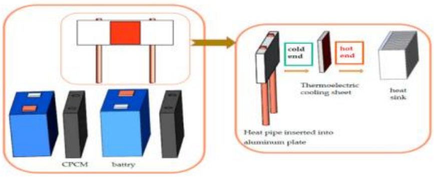


Fig. 57. Thermal management schematic diagram of a thermoelectric combined with CPCM [89].

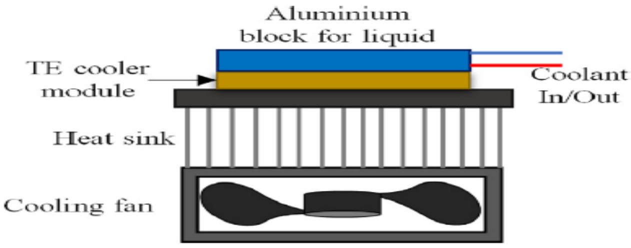


Fig. 58. Schematic illustration of the single used unit of TEC system for BTMS [90].

Sarawut et al. [91] Experimentally investigated thermoelectric cooling combined with a thermoelectric ferrofluid cooling module and the Effects of the relevant parameters: hot and cold side flow rates (0.03-0.05 m3/hr.). Supplied voltage through thermoelectric (8-12 V) (see Fig.58). It is found that the TEC system affects the battery pack cooling and gives the battery temperature below 30°C. Three °C decreased the maximum temperature of the average battery cell temperature to 5°C, and the obtained maximum temperature difference is below 3°C.

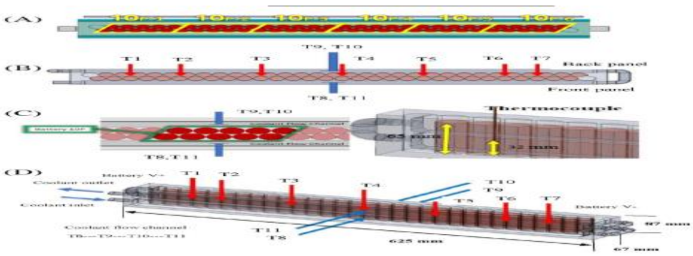


FIG .59 Details of A, the battery pack. B, the temperature battery measurement positions. C is the position of the vertical temperature battery measurement, and D is the place of the coolant temperature measurement flowing through the battery pack [91].

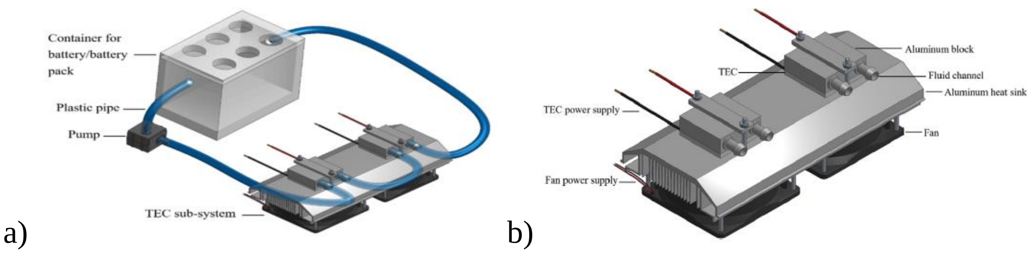
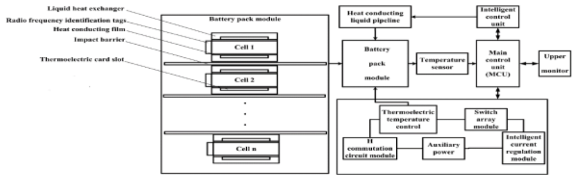
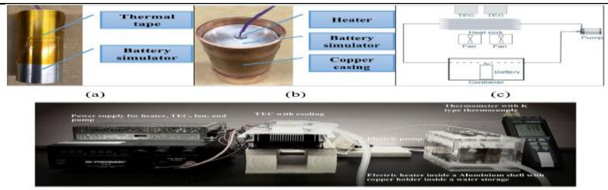
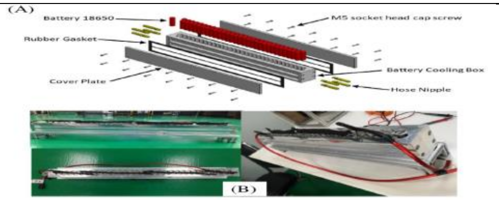
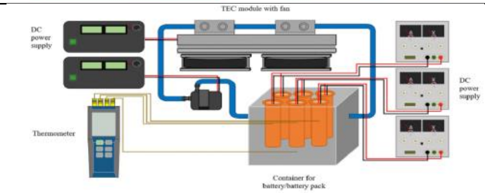


Fig. 60. a) Illustration of the coolant flow path, b) Structure of the TEC sub-system [92]

You Lyu et al. [92] Experimentally investigated thermoelectric cooling for a battery pack design in a copper holder and Solid-state thermoelectric refrigeration with H.P. systems (see Fig. 59) . The battery pack temperature reached under 60 °C during a discharge condition with a 50 V input, considered an extreme condition for battery operation.

Table 8 Summarize the studies modules with design Figures, specifications, and operating conditions using a Thermo-electric Module for cooling in Li-ion batteries.

Table 8 Summary of Studies Thermo-electric Module Cooling in Li-ion Batteries.

Author (Year)	Design		Module Specification		Operating condition	Important results	
	Description	Picture	Battery capacity (Ah)	Thermo-electric Module Voltage(v)	Battery load c-rate	Tamb (°C)	Tmax (°C)
Chuan-Wei Zhang [93][2018]	control procedure		20Ah	12	3c	25	55
Chuan-Wei Zhang [89][2019]	Test platform.		3.6/100Ah	15.2	3c	25	49
You Lyu [106] [2019]	Experiment setup of the proposed system.		10Ah	12	6C	20-25	43
Sarawut [91][2021]	Details of the the battery cooling module		6Ah	8-12	3c	25	40
You Lyu [92][2021]	Schematic presentation of an overview of the experiment setup		6Ah	10	3000s	22	55

2.6 Hybrid BTMS Cooling Systems

A hybrid BTMS is a combination of two or more BTMSs. Different BTMSs have their advantages and disadvantages. The hybrid BTMS system can combine these advantages and reach better thermal performance. Otherwise, hybrid BTMS may involve some problems with volume, ease of use, weight, energy consumption, cost, and maintenance. Hybrid BTMS methods adopt different basic methods designed to meet E.V.s' requirements. TEC and heat pipe cooling methods are usually combined with other types of cooling to enhance the properties, as mentioned before.

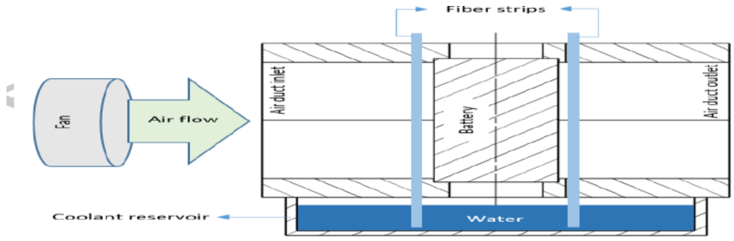


Fig. 61 hybrid cooling channel design [94].

2.6.1 Hybrid BTMS Cooling Systems Simulation and Experimental Studies

For example, several studies have been undertaken to benefit from the advantages of hybrid air, liquid, and PCM cooling systems. In 2018, Yuyang Wei et al. [94] experimentally studied the design of a simple air-cooling duct that enhanced water vaporization by convection to achieve adequate cooling (see Fig.60) . The result showed that hybrid cooling decreased the maximum surface temperature from 55°C to only 30.5°C (73.5% reduction). The temperature uniformity decreased from 13.5°C to only 2.1°C (85.7% reduction) in non-uniformity.

Peng Qin et al. [95] studied integrated PCM hybrid cooling systems design optimized with forced air (see Fig.61) . The results showed that PCM's thermal performance under the hybrid mode is superior to that under the only PCM mode, with the influence of maximum temperature under 50°C and temperature different of 5°C.

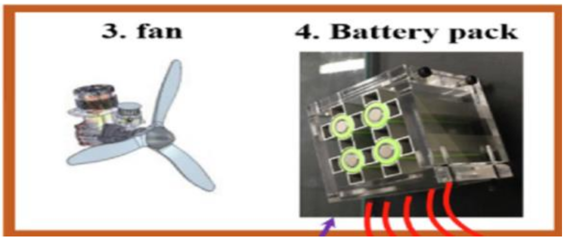


Fig. 62. describes the proposed BTMS [95].

Many types of research have been experimentally and simulated studied to enhance the PCM with liquid cooling system [96-114] due to its better thermal properties and more efficient cooling, for example. Fengxian Wang[111] presented an experimental and numerical study based on simulative investigations on a commercial organic PCM (OP28E), which was compounded with water to prepare two nano-emulsions PCM with different concentrations of OP28E, ten wt%, and 20 wt% (see Fig.62). The results showed that Tmax and Tmax were 1.1°C and 0.8°C lower than those based on water, respectively, when a 10 wt% OP28E nano-emulsion was utilized with a flow rate of 200 mL min-1.

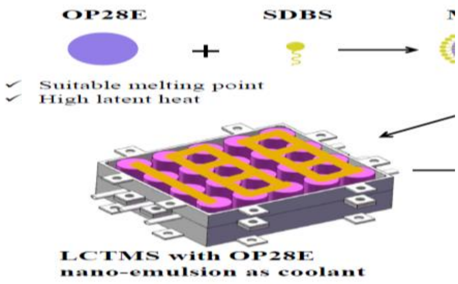


Fig.63. BTMS with OP28E nano-emulsion as coolant [111].

Jiahao Cao et al.[112]presented an experimental and numerical study based on Liquid cooling with PCM for cylindrical Li-ion batteries(see Fig.63). The result showed that PCM thermo-physical properties significantly impact battery temperature, especially at high-current discharges. CPCM (RT44HC) can reduce Tmax from more than 50°C to 44°C and 42°C.

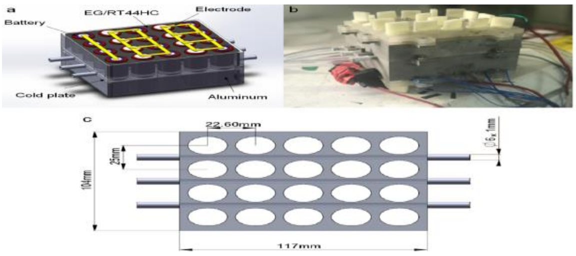


Fig. 64. The battery pack and the cold plate: (a) model diagram of the battery pack; (b) the battery pack; (c) model diagram of the cold plate [112].

Quantity et al. [113] designed the cooling structure of a LIB coupled liquid cooling with PCM, focused on the coolant's flow rate and the cooling pipe's position, and investigated their influences on the operating temperature (see Fig.64). The results showed that a flow rate of 0.09 m/s was utilized in this system. The maximum temperature deviation was less than 0.25%, comparable to 0.1 m/s. More heat can be removed by the unit mass coolant when using the appropriately selected flow rate. Appropriate cross-section selection with PCM can reduce the temperature difference to near 5 K.

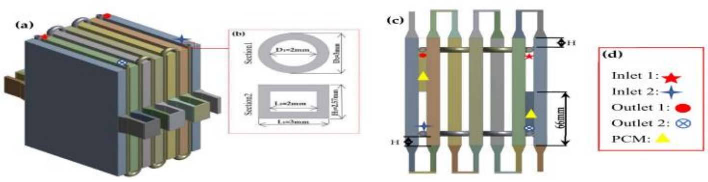


Fig.65. Schematic of liquid cooling: (a) layout of pipes of 1P7S battery pack (c) movement of pipe position [113].

Wen Yang et al. [115] experimentally designed a composite BTMS using mini-channel liquid cooling and air cooling (see Fig.65). The findings demonstrated that maximum temperature and temperature differential decrease when water intake flow rate and power consumption increase. When the water inlet flow rate is 3 × 10−4 kg·s−1, increasing the cooling tube and mini-channel could slightly improve the cooling performance. The temperature difference would remain within 4.13 °C, and the maximum temperature would decrease to 31.98°C. Moreover, the extra air cooling at the velocity of 4 m·s−1 could Reduce the maximum temperature, and at 80% DOD, the battery module's temperature difference decreased by 2.22 °C and 2.04 °C, respectively.

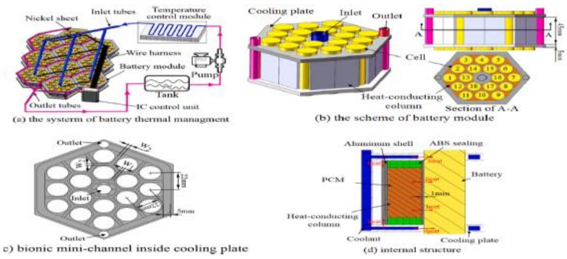


Fig. 66. Scheme of battery thermal management system [115].

Wen Yang et al. [99] simulated a novel BTMS-like honeycomb. A hexagonal cooling plate with bionic liquid mini-channel and PCM (see Fig.66). The battery module's maximum temperature and the temperature difference are stabilized between 39.0 °C and 3.5 °C.

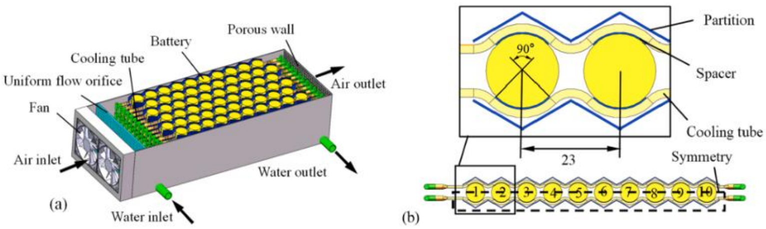


Fig. 67. Scheme of battery thermal management system [99].

Zhang et al. [116] studied the hybrid cooling of PCM with liquid cooling to improve the cooling properties. Fig.67 shows that the proposed BTMS consists of PCM, an aluminum plate, and a water-cooling channel. PCM and LIBs are designed as simple sandwich structures; both sides of the battery are covered with PCM to absorb the heat generated by the battery. It found that the maximum temperature of the battery can be controlled at around 39℃, and the PCM-based BTMS can control the temperature difference of the battery within one ℃. Table.10 Summarizes the studies modules with design Figures, specifications, and operating conditions for hybrid cooling in Li-ion batteries (PCM+ air/liquid).

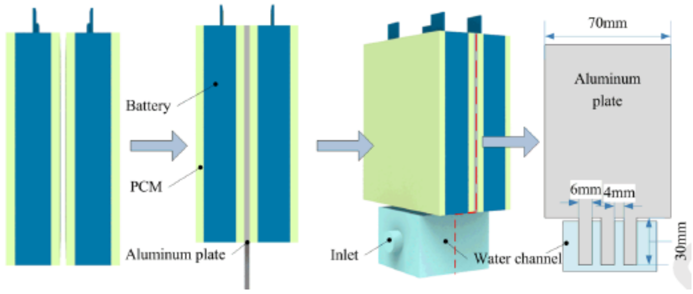
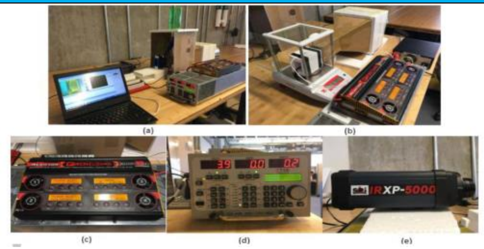
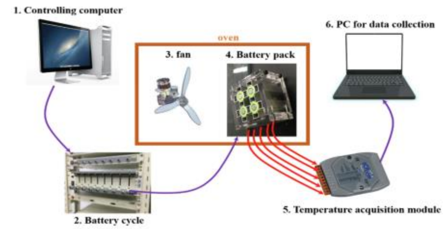
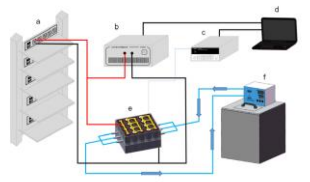
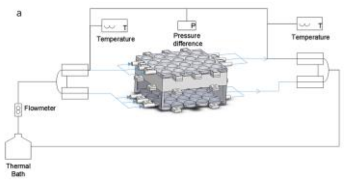
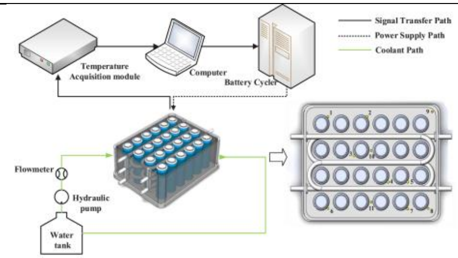
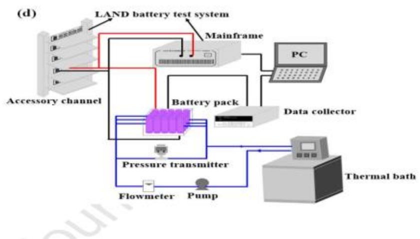
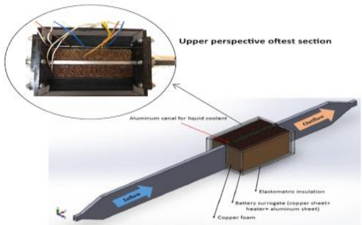
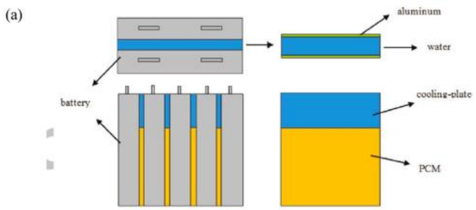
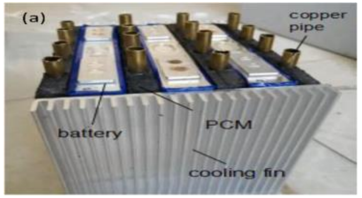
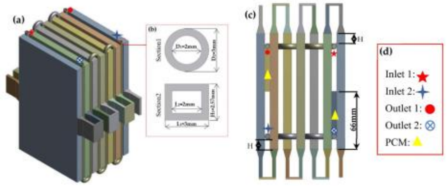
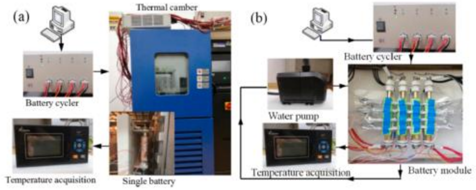
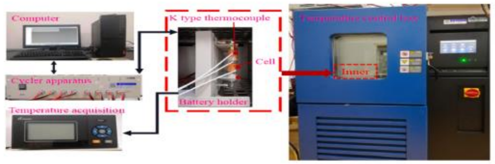
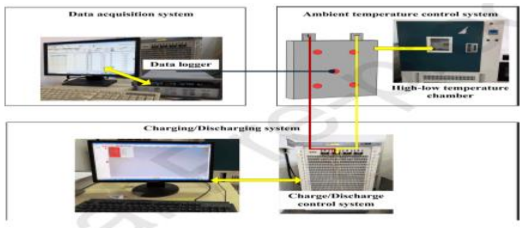


Fig. 68. Schematic of PCM-LIB sandwich structure [116].

Table 10 Summary of studies on hybrid cooling in Li-ion batteries (PCM+ air/liquid).

Author (Year)	Design		Description			Operating condition		Important results	
	Combination	Picture	Li-ion Battery	Battery capacity (Ah)	PCM and melting temperature	Battery load	Tamb (°C)	Tmax (°C)	ΔTmax (°C)
Yuyang Wei [94][2018]	a simple air-cooling with water vaporization by convection		LIBs	5.2		1c	20	33	5
Peng Qin [95][2019]	forced-air convection and PCM		(4) 18650 LIBs	2.6	paraffin wax (RT56) 60 °C	3c	27	50	5
Jiahao Cao [112][2019]	Liquid cooling with PCM	 Fig. 2. Diagram of the experiment: (a) battery circulation auxiliary channel; (b) battery cycle tester CT2001D; (c) Agilent 34970A; (d) computer; (e) battery pack; (f) constant low-temperature bath DC-2006.	(20) 18650 LIBs	2.6		3c	30	42	3.5
Ziye Ling [117][2019]	liquid cooling with (PCM) using (RSM)		(20) 18650 LIBs	2.6	expanded graphite (E.G.) 44c	1.5 c	30	37	3

Depeng Kong [118][2019]	PCM and optimized controllable liquid cooling		LIBs (6S4P) 21,700	4Ah	lipid and expanded graphite (E.G.).	3c	30	42	5
Fengxian Wang[111] [2020]	(PCM) nano-emulsions with enhanced liquid cooling		5S4P battery pack 10.4 Ah	2.6 Ah	Water 10 wt% OP28E nano-emulsions 20 wt% OP28E nano-emulsions	2c	32 30 28	48 45 43	4 3 2
Mehrdad Kiani [119][2020]	PCM and Al2O3/AgO/CuO nanofluids and		Prismatic battery	9Ah	Paraffin (37.8–44.2)	3c	25	51.4	5
G.R. Molaeimanesh [120][2020]	PCM and water-cooling channels		(12) LIBs 18650	2.6 Ah	RT27	3c	20	33	

Ziqiang Liu [121][2021]	composite PCM and liquid cooling		5S4P battery pack 10.4 Ah	65Ah	paraffin/expanded graphite (E.G.)/high-density polyethylene	3c	33	59,5	16.3
Quanyi Li [113][2021]	Water and PCM		1P7S battery pack	200 W 3v	29.6	200w	27	37	5
Wen Yang [115][2020]	mini-channel liquid cooling and air cooling		60 LIBs	2		4c	20	33	4.33
Wen Yang [99] [2021]	mini-channel liquid cooling with PCM and air cooling		60 LIBs	2		4c	35.2	39	3.5
Zhang Wen [2021] [116]	phase change material and liquid cooling		3.6V battery	25Ah	33-37	5c	27	39	1.5

3. Outlook Directions for the Future Work

The transportation system will mainly depend on Electric Vehicles in the future. Therefore, improving Li-ion batteries' power and energy density is the most needed. A proper battery cooling system is essential to battery performance and life; therefore, BTMS is a hotspot for conducting research. There are plenty of directions to improve the thermal performance of existing BTMSs. The following is the most compelling research scope in this area.

3.1 High Ambient Temperature

With the fast-ongoing global warming and increase in atmospheric temperature, EVs of tomorrow will need to be operated under harsh ambient conditions. Even in regions like the Arabian Gulf, the ambient temperature changes by more than 2℃ to reach more than 45℃ in summer (see Fig. 68)[122]. Almost all studies simultaneously start their ambient temperature with a range of 27°C-35°C (see Fig. 69). Many zone temperatures worldwide exceed 45°C. Therefore, there is still a need to study the start temperature experimentally with more than 45°C and 50°C to simulate using electric vehicles in the hot zone in the world at the hot weather zone causing overheating and thermal runaway phenomena.

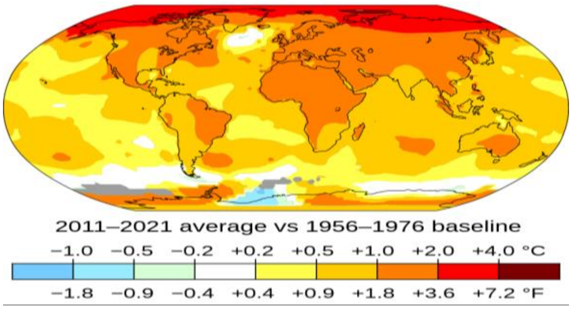


Fig. 69 Changes in the average surface air temperatures from 2011 to 2021 relative to the average between 1956 and 1976 [122].

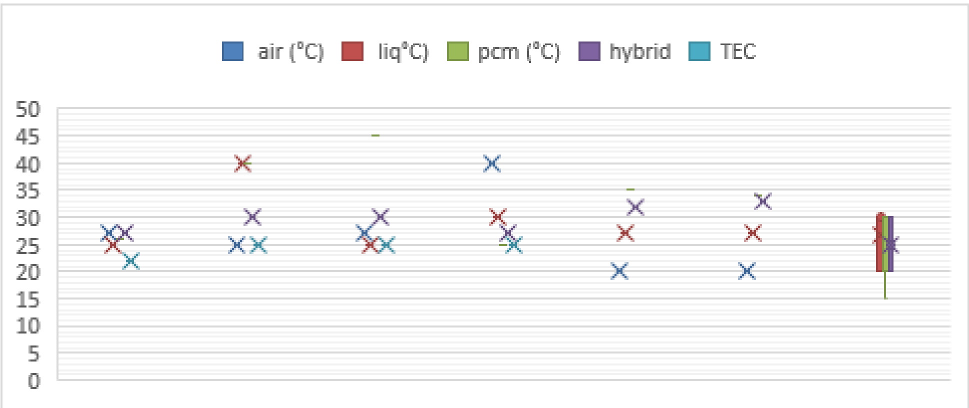


Fig. 70. Ambient temperature of different cooling studies.

3.2 Battery Packing and Isolation.

Battery packing is critically required to Control ambient battery temperature, vibration, and pressure to maximize energy capacity. Battery packing maintained ambient temperature with a safe operation. The vibration frequencies of the battery pack should also be suppressed to avoid resonance. The scope of the search still needs more experimental and simulative packing studies to maintain the ambient temperatures under 40^{o}c and prevent the battery from cracking or short welding spots due to high vibration, causing thermal runaway catastrophic phenomena.

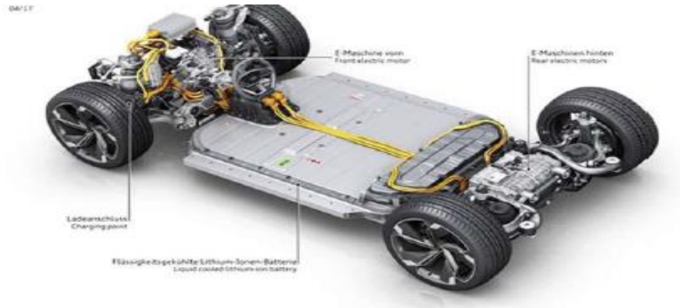


Fig.71. Placement of lithium-ion battery pack in GM Chevrolet Volt [123]

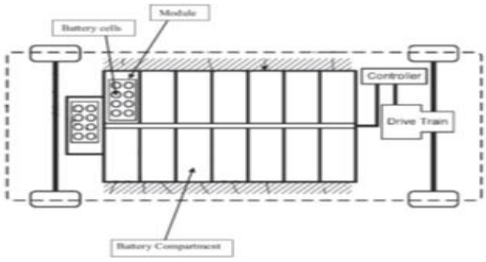


Fig.72. A robust battery pack with one battery module in each battery pack compartment[123]

3.3 Thermal Runaway (TR).

Thermal runaway is the most severe condition of BTMS. Thermal runaways are still a hotspot for further research in this area. Many types of research have been published to prevent the battery packs from going into thermal runaways. Analytical solutions to these problems are too complex; hence, numerical simulations and experimental studies can be performed along with the experimentations.

3.4 Air and water cooling.

Air and water are the most popular BTMS cooling. And still the only commercialized fluids for EV batteries. Many designs of BTMS with different airflows are reported in the literature. Similarly, tube cooling, cold plates, and mini channels are studied for liquid cooling systems. Using different coolant materials or heat transfer mediums is challenging for any BTMS cooling medium. Water and ethylene glycol are the coolants that have been studied the most. A new coolant can also be identified for liquid cooling. Nanoparticles can be added to the fluid to enhance its thermal properties of the fluid.

3.5 Phase Change Materials.

Although PCM is still not applied to any practical EV due to its limitations, many researchers investigated PCM for BTMS cooling. Limited-service life and leakage problems are the biggest obstacles to implementing PCM in automotive applications. There is a scope of research to find methods for enhancing the thermal performance of pure and composite PCMs.

3.6 Heat pipes.

Water and acetone are the most commonly studied coolants for HP cooling systems. Using Different fluids can enhance thermal performance. HP is mainly studied with prismatic or pouch cells. The cylindrical battery HP application to cells is worth exploring for future research. Experimentations and simulations for large battery packs/ modules can be performed for more effective conclusions.

3.7 Cost Minimization.

Cost is an essential parameter for commercial purposes of active and passive BTMSs. Reducing the battery pack's volume and weight is a vital cost-reduction consideration. Many reviews of research work on BTMS studied cost minimization, its advantages and disadvantages, and changes in conventional systems. Much research is still needed to investigate and develop novel cooling techniques with minimum cost for better thermal management of Li-ion batteries.

The direction of future work presented in this review will assist the researchers in focusing on enhancing the conventional BTMS and their improvement for commercial purposes.

4. Conclusion

Excellent control strategies of BTMSs can significantly improve Li-ion batteries' performances, ensure a long cycle life, and prevent thermal runaway from occurring to enhance thermal performance. The main contributions of this review paper are as follows:

(1) the characteristics related to the thermal performances of Li-ion batteries were analyzed, and problems related to heat dissipation in batteries were summarized. Moreover, the thermal performance stabilities of LIB materials and the thermal hazards, when thermal runaway occurs were also reviewed.

(2) The currently applied technologies for BTMS cooling were introduced (air cooling- liquid cooling – direct refrigeration cooling- PCM cooling-heat pipe cooling, and a combination of them). The merits and demerits of the various cooling methods were analyzed, and many optimization methods were compared. In addition, BTMS needs to design an appropriate temperature control strategy to improve the system's performance.

(3) summarized the essential evaluation parameters from previous research, which can be used as evaluation criteria for BTMS. This will guide the optimization of the design of BTMS from different points of view and help acquire the most appropriate BTMS. However, many types of research have been published using various BTMS methods in the last decade. Most of this paper didn't study the high ambient temperature, which is too essential in the hot zone country which can Cause many hazard problems and maybe need a different system to cool the ambient temperate of the battery to the desired input temperature of BTMS, which require more load on the system cause more energy waste.

References

[1] J.A. Sanguesa, V. Torres-Sanz, P. Garrido, F.J. Martinez, J.M. Marquez-Barja, A Review on Electric Vehicles: Technologies and Challenges, Publisher, City, 2021.

[2] J. Lin, X. Liu, S. Li, C. Zhang, S. Yang, A review on recent progress, challenges, and perspective of battery thermal management system, Publisher, City, 2021.

[3] D. Keiner, M. Ram, L.D.S.N.S. Barbosa, D. Bogdanov, C. Breyer, Cost optimal self-consumption of PV prosumers with stationary batteries, heat pumps, thermal energy storage and electric vehicles across the world up to 2050, Publisher, City, 2019.

[4] J. Quintiere, Literature Review: Packaging Technique to Defeat Fires and Explosions due to Lithium-ion and Related High-Energy-Density Batteries, Publisher, City, 2020.

[5] N. Ghaeminezhad, Z. Wang, Q. Ouyang, A Review on lithium-ion battery thermal management system techniques: A control-oriented analysis, Publisher, City, 2023.

[6] P.M. Montanari, D.N. Hummes, J.D. Hunt, B.B.D. Hunt, P.S. Schneider, A Comparative Study of Different Battery Geometries Used in Electric Vehicles, Publisher, City, 2022.

[7] D. Brzezinska, P. Bryant, Performance-Based Analysis in Evaluation of Safety in Car Parks under Electric Vehicle Fire Conditions, Publisher, City, 2022.

[8] M. Wayland, Ford F-150 Lightning fire footage highlights a growing EV risk, in CNBC, CNBC, autos, 2023.

[9] W. Wu, S. Wang, W. Wu, K. Chen, S. Hong, Y. Lai, A critical review of battery thermal performance and liquid based battery thermal management, Publisher, City, 2019.

[10] J.E.d. Silva, J. Urbanetz Junior, Converting a Conventional Vehicle into an Electric Vehicle (EV), Publisher, City, 2019.
[11] A. König, L. Nicoletti, D. Schröder, S. Wolff, A. Waclaw, M. Lienkamp, An Overview of Parameter and Cost for Battery Electric Vehicles, Publisher, City, 2021.
[12] Q. Wang, B. Jiang, B. Li, Y. Yan, A critical review of thermal management models and solutions of lithium-ion batteries for the development of pure electric vehicles, Publisher, City, 2016.
[13] S. Arora, Selection of thermal management system for modular battery packs of electric vehicles: A review of existing and emerging technologies, Publisher, City, 2018.
[14] A. Carnovale, Investigation into the effect of thermal management on the capacity fade of lithium-ion batteries, in, University of Waterloo, 2017.
[15] C. Aswin Karthik, P. Kalita, X. Cui, X. Peng, Thermal management for prevention of failures of lithium ion battery packs in electric vehicles: A review and critical future aspects, Publisher, City, 2020.
[16] D. Deng, Li-ion batteries: basics, progress, and challenges, Publisher, City, 2015.
[17] Y. Salami, M. Aghabeigi, F. Imani, A Review on Electric Vehicle Battery Thermal Management Systems, Merits and Demerits, Publisher, City.
[18] Y. Salami, A Review on Electric Vehicle Battery Thermal Management Systems, Merits, and Demerits, in: F.I. Mahya Aghabeigi (Ed.) 8th Conference on Thermal Power Plants, Toosi University of Technology, Tehran, Iran, 2021.
[19] S. Durgam, P. Datir, O. Tawase, D. Savant, G. Tapkir, R.M. Warkhedkar, N.M. Gawai, Materials selection for hybrid and electric vehicle battery pack thermal management: A review, Publisher, City, 2021.
[20] S. Yang, A Review of Lithium-Ion Battery Thermal Management System Strategies and the Evaluate Criteria, Publisher, City, 2019.
[21] F. PRA, Electric Vehicle Enhanced Range, Lifetime And Safety Through INGenious battery management Publisher, City, 2020.
[22] X. Zhang, Z. Li, L. Luo, Y. Fan, Z. Du, A review on thermal management of lithium-ion batteries for electric vehicles, Publisher, City, 2022.
[23] P.R. Tete, M.M. Gupta, S.S. Joshi, Developments in battery thermal management systems for electric vehicles: A technical review, Publisher, City, 2021.
[24] G. Xia, L. Cao, G. Bi, A review on battery thermal management in electric vehicle application, Publisher, City, 2017.
[25] V. Mali, R. Saxena, K. Kumar, A. Kalam, B. Tripathi, Review on battery thermal management systems for energy-efficient electric vehicles, Publisher, City, 2021.
[26] A.H. Hasani, M. Mansor, V. Kumaran, A.W.M. Zuhdi, Y.J. Ying, M.A. Hannan, F.A. Hamid, M.S.A. Rahman, N.A. Salim, Thermal behavior of lithium-ion battery in microgrid application: Impact and management system, Publisher, City, 2020.
[27] J. Kim, J. Oh, H. Lee, Review on battery thermal management system for electric vehicles, Publisher, City, 2019.
[28] L. He, H. Jing, Y. Zhang, P. Li, Z. Gu, Review of thermal management system for battery electric vehicle, Publisher, City, 2023.
[29] J. Li, Z. Zhu, Battery thermal management systems of electric vehicles, in, 2014.
[30] E. Hosseinzadeh, R. Genieser, D. Worwood, A. Barai, J. Marco, P. Jennings, A systematic approach for electrochemical-thermal modeling of a large format lithium-ion battery for electric vehicle application, Publisher, City, 2018.
[31] M. Khan, M. Swierczynski, S. Kær, Towards an Ultimate Battery Thermal Management System: A Review, Publisher, City, 2017.
[32] H. Liu, Z. Wei, W. He, J. Zhao, Thermal issues about Li-ion batteries and recent progress in battery thermal management systems: A review, Publisher, City, 2017.
[33] G. Zhao, X. Wang, M. Negnevitsky, H. Zhang, A review of air-cooling battery thermal management systems for electric and hybrid electric vehicles, Publisher, City, 2021.
[34] O. Kalaf, D. Solyali, M. Asmael, Q. Zeeshan, B. Safaei, A. Askir, Experimental and simulation study of

liquid coolant battery thermal management system for electric vehicles: A review, Publisher, City, 2020.
[35] M. Malik, I. Dincer, M.A. Rosen, Review on use of phase change materials in battery thermal management for electric and hybrid electric vehicles, Publisher, City, 2016.
[36] G. Murali, G.S.N. Sravya, J. Jaya, V. Naga Vamsi, A review on hybrid thermal management of battery packs and it's cooling performance by enhanced PCM, Publisher, City, 2021.
[37] Z. Ling, Z. Zhang, G. Shi, X. Fang, L. Wang, X. Gao, Y. Fang, T. Xu, S. Wang, X. Liu, Review on thermal management systems using phase change materials for electronic components, Li-ion batteries and photovoltaic modules, Publisher, City, 2014.
[38] D.K. Sharma, A. Prabhakar, A review on air cooled and air centric hybrid thermal management techniques for Li-ion battery packs in electric vehicles, Publisher, City, 2021.
[39] V.G. Choudhari, D.A.S. Dhoble, T.M. Sathe, A review on effect of heat generation and various thermal management systems for lithium ion battery used for electric vehicle, Publisher, City, 2020.
[40] A. Borchers, T. Pieler, Programming pluripotent precursor cells derived from Xenopus embryos to generate specific tissues and organs, Publisher, City, 2010.
[41] C. Zhao, B. Zhang, Y. Zheng, S. Huang, T. Yan, X. Liu, Hybrid Battery Thermal Management System in Electrical Vehicles: A Review, Publisher, City, 2020.
[42] K. Chen, M. Song, W. Wei, S. Wang, Structure optimization of parallel air-cooled battery thermal management system with U-type flow for cooling efficiency improvement, Publisher, City, 2018.
[43] S. Hong, X. Zhang, K. Chen, S. Wang, Design of flow configuration for parallel air-cooled battery thermal management system with secondary vent, Publisher, City, 2018.
[44] Y. Fan, Y. Bao, C. Ling, Y. Chu, X. Tan, S. Yang, Experimental study on the thermal management performance of air cooling for high energy density cylindrical lithium-ion batteries, Publisher, City, 2019.
[45] H. Park, A design of air flow configuration for cooling lithium ion battery in hybrid electric vehicles, Publisher, City, 2013.
[46] T.I.C.B.a.F. Mariasiu, Modeling Approach of an Air-Based Battery Thermal Management System for an Electric Vehicle, in Automotive Engineering and Transports Department, Technical University of Cluj-Napoca, Bdul, Muncii 103-105, applied sciences, 2021.
[47] Y. Gao, Numerical Study on Thermal Management of Air-Cooling Model for Diamond, Triangular and Rectangular Lithium-Ion Batteries of Electric Vehicles, Publisher, City, 2022, 10, 1104.
[48] C. Yang, H. Xi, M. Wang, Structure optimization of air cooling battery thermal management system based on lithium-ion battery, Publisher, City, 2023.
[49] J.H.a.S.H. Chanyang Kim Evaluation of Spoiler Model Based on Air Cooling on Lithium-Ion Battery Pack Temperature Uniformity, Publisher, City, 2022.
[50] F. PRA, Electric Vehicle Enhanced Range, Lifetime And Safety Through INGenious battery management, Publisher, City, 2020.
[51] T. Deng, G. Zhang, Y. Ran, Study on thermal management of rectangular Li-ion battery with serpentine-channel cold plate, Publisher, City, 2018.
[52] J. E, D. Han, A. Qiu, H. Zhu, Y. Deng, J. Chen, X. Zhao, W. Zuo, H. Wang, J. Chen, Q. Peng, Orthogonal experimental design of liquid-cooling structure on the cooling effect of a liquid-cooled battery thermal management system, Publisher, City, 2018.
[53] C. Zhao, W. Cao, T. Dong, F. Jiang, Thermal behavior study of discharging/charging cylindrical lithium-ion battery module cooled by channeled liquid flow, Publisher, City, 2018.
[54] M. Malik, I. Dincer, M.A. Rosen, M. Mathew, M. Fowler, Thermal and electrical performance evaluations of series connected Li-ion batteries in a pack with liquid cooling, Publisher, City, 2018.
[55] L.H. Saw, H.M. Poon, H.S. Thiam, Z. Cai, W.T. Chong, N.A. Pambudi, Y.J. King, Novel thermal management system using mist cooling for lithium-ion battery packs, Publisher, City, 2018.
[56] S. Chen, N. Bao, L. Gao, X. Peng, A. Garg, An experimental investigation of liquid cooling scheduling for a battery module, Publisher, City, 2020.
[57] T. Deng, G. Zhang, Y. Ran, P. Liu, Thermal performance of lithium ion battery pack by using cold plate, Publisher, City, 2019.

[58] H. Wang, T. Tao, J. Xu, X. Mei, X. Liu, P. Gou, Cooling capacity of a novel modular liquid-cooled battery thermal management system for cylindrical lithium ion batteries, Publisher, City, 2020.

[59] P. Dančová, J. Bohacek, J. Hvozda, K. Mraz, A. Vakhrushev, E. Karimi-Sibaki, J. Novosád, J. Pulec, Polymeric hollow fibers: a modular heat exchanger for thermal management systems of battery modules in electric vehicles, Publisher, City, 2022.

[60] J. Heutter, Audi unveils 2019 e-tron, its steel-and-aluminum electric SUV, in Repairer driven News, Repairer Driven NewsRepairer Driven News,". 2018.

[61] M.-B.G. Media, Mercedes-Benz S-Class S 400 HYBRID: Compared with conventional nickel metal hydride batteries, the lithium-ion battery features a higher electric power density and better electric efficiency combined with more compact dimensions and lower weight, in Mercedes-Benz Group Media, 2009.

[62] M. Al-Zareer, I. Dincer, M.A. Rosen, Novel thermal management system using boiling cooling for high-powered lithium-ion battery packs for hybrid electric vehicles, Publisher, City, 2017.

[63] M. Al-Zareer, I. Dincer, M.A. Rosen, Development and evaluation of new ammonia boiling based battery thermal management system, Publisher, City, 2018.

[64] S.H. Hong, D.S. Jang, S. Park, S. Yun, Y. Kim, Thermal performance of direct two-phase refrigerant cooling for lithium-ion batteries in electric vehicles, Publisher, City, 2020.

[65] Z. Ling, J. Chen, X. Fang, Z. Zhang, T. Xu, X. Gao, S. Wang, Experimental and numerical investigation of the application of phase change materials in a simulative power batteries thermal management system, Publisher, City, 2014.

[66] A. Wazeer, A. Das, C. Abeykoon, A. Sinha, A. Karmakar, Phase Change Materials for Battery Thermal Management of Electric and Hybrid Vehicles: A Review, Publisher, City, 2022.

[67] R. Kizilel, A. Lateef, R. Sabbah, M.M. Farid, J.R. Selman, S. Al-Hallaj, Passive control of temperature excursion and uniformity in high-energy Li-ion battery packs at high current and ambient temperature, Publisher, City, 2008.

[68] S. Zhang, R. Zhao, J. Liu, J. Gu, Investigation on a hydrogel based passive thermal management system for lithium ion batteries, Publisher, City, 2014.

[69] C.-V. Hémery, F. Pra, J.-F. Robin, P. Marty, Experimental performances of a battery thermal management system using a phase change material, Publisher, City, 2014.

[70] Z.G. Qu, W.Q. Li, W.Q. Tao, Numerical model of the passive thermal management system for high-power lithium ion battery by using porous metal foam saturated with phase change material, Publisher, City, 2014.

[71] R. Zhao, J. Gu, J. Liu, Optimization of a phase change material based internal cooling system for cylindrical Li-ion battery pack and a hybrid cooling design, Publisher, City, 2017.

[72] P. Ping, R. Peng, D. Kong, G. Chen, J. Wen, Investigation on thermal management performance of PCM-fin structure for Li-ion battery module in high-temperature environment, Publisher, City, 2018.

[73] Y. Li, Y. Du, T. Xu, H. Wu, X. Zhou, Z. Ling, Z. Zhang, Optimization of thermal management system for Li-ion batteries using phase change material, Publisher, City, 2018.

[74] Z. Wang, X. Li, G. Zhang, Y. Lv, J. He, J. Luo, C. Yang, C. Yang, Experimental study of a passive thermal management system for three types of battery using copper foam saturated with phase change materials, Publisher, City, 2017.

[75] X. Wang, Y. Xie, R. Day, H. Wu, Z. Hu, J. Zhu, D. Wen, Performance analysis of a novel thermal management system with composite phase change material for a lithium-ion battery pack, Publisher, City, 2018.

[76] F. Samimi, A. Babapoor, M. Azizi, G. Karimi, Thermal management analysis of a Li-ion battery cell using phase change material loaded with carbon fibers, Publisher, City, 2016.

[77] D. Zou, X. Ma, X. Liu, P. Zheng, Y. Hu, Thermal performance enhancement of composite phase change materials (PCM) using graphene and carbon nanotubes as additives for the potential application in lithium-ion power battery, Publisher, City, 2018.

[78] X. Yang, Y.Y. Yan, D. Mullen, Recent developments of lightweight, high performance heat pipes, Publisher, City, 2012.

[79] Y. Huang, Y. Tang, W. Yuan, G. Fang, Y. Yang, X. Zhang, Y. Wu, Y. Yuan, C. Wang, J. Li, Challenges

and recent progress in thermal management with heat pipes for lithium-ion power batteries in electric vehicles, Publisher, City, 2021.
[80] Y. Li, G. Chang, Y. Xu, J. Zhang, W. Zhao, A Review of MHP Technology and Its Research Status in Cooling of Li-Ion Power Battery and PEMFC, Publisher, City, 2020.
[81] R. Zhao, J. Gu, J. Liu, An experimental study of heat pipe thermal management system with wet cooling method for lithium ion batteries, Publisher, City, 2015.
[82] Z.Y. Jiang, Z.G. Qu, Lithium–ion battery thermal management using heat pipe and phase change material during discharge–charge cycle: A comprehensive numerical study, Publisher, City, 2019.
[83] W. Liu, Z. Jia, Y. Luo, W. Xie, T. Deng, Experimental investigation on thermal management of cylindrical Li-ion battery pack based on vapor chamber combined with fin structure, Publisher, City, 2019.
[84] T. Wei, X. Xiaoming, D. Hua, G. Yaohua, L. Jicheng, W. Hongchao, Sensitivity Analysis of the Battery Thermal Management System with a Reciprocating Cooling Strategy Combined with a Flat Heat Pipe, Publisher, City, 2020.
[85] N. Mei, X. Xu, R. Li, Heat Dissipation Analysis on the Liquid Cooling System Coupled with a Flat Heat Pipe of a Lithium-Ion Battery, Publisher, City, 2020.
[86] H. Behi, M. Behi, D. Karimi, J. Jaguemont, M. Ghanbarpour, M. Behnia, M. Berecibar, J. Van Mierlo, Heat pipe air-cooled thermal management system for lithium-ion batteries: High power applications, Publisher, City, 2021.
[87] C. Zhang, Z. Xia, B. Wang, H. Gao, S. Chen, S. Zong, K. Luo, A Li-Ion Battery Thermal Management System Combining a Heat Pipe and Thermoelectric Cooler, Publisher, City, 2020.
[88] X. Li, Z. Zhong, J. Luo, Z. Wang, W. Yuan, G. Zhang, C. Yang, C. Yang, Experimental Investigation on a Thermoelectric Cooler for Thermal Management of a Lithium-Ion Battery Module, Publisher, City, 2019.
[89] C.-W. Zhang, S.-R. Chen, H.-B. Gao, K.-J. Xu, Z. Xia, S.-T. Li, Study of Thermal Management System Using Composite Phase Change Materials and Thermoelectric Cooling Sheet for Power Battery Pack, Publisher, City, 2019.
[90] Y. Lyu, A.R.M. Siddique, S.H. Majid, M. Biglarbegian, S.A. Gadsden, S. Mahmud, Electric vehicle battery thermal management system with thermoelectric cooling, Publisher, City, 2019.
[91] S. Sirikasemsuk, S. Wiriyasart, P. Naphon, N. Naphon, Thermal cooling characteristics of Li-ion battery pack with thermoelectric ferrofluid cooling module, Publisher, City, 2021.
[92] Y. Lyu, A.R.M. Siddique, S.A. Gadsden, S. Mahmud, Experimental investigation of thermoelectric cooling for a new battery pack design in a copper holder, Publisher, City, 2021.
[93] C.-W. Zhang, K.-J. Xu, L.-Y. Li, M.-Z. Yang, H.-B. Gao, S.-R. Chen, Study on a Battery Thermal Management System Based on a Thermoelectric Effect, Publisher, City, 2018.
[94] Y. Wei, M. Agelin-Chaab, Experimental investigation of a novel hybrid cooling method for lithium-ion batteries, Publisher, City, 2018.
[95] P. Qin, M. Liao, D. Zhang, Y. Liu, J. Sun, Q. Wang, Experimental and numerical study on a novel hybrid battery thermal management system integrated forced-air convection and phase change material, Publisher, City, 2019.
[96] L. Song, H. Zhang, C. Yang, Thermal analysis of conjugated cooling configurations using phase change material and liquid cooling techniques for a battery module, Publisher, City, 2019.
[97] X. Wu, Z. Zhu, H. Zhang, S. Xu, Y. Fang, Z. Yan, Structural optimization of light-weight battery module based on hybrid liquid cooling with high latent heat PCM, Publisher, City, 2020.
[98] N. Yang, M. Wang, J. Wang, L. Wang, Y. Fu, A Model-Based Assessment of Controllable Phase Change Materials/Liquid Coupled Cooling System for the Power Lithium-Ion Battery Pack, Publisher, City, 2021.
[99] W. Yang, F. Zhou, Y. Liu, S. Xu, X. Chen, Thermal performance of honeycomb-like battery thermal management system with bionic liquid mini-channel and phase change materials for cylindrical lithium-ion battery, Publisher, City, 2021.
[100] F. Bai, M. Chen, W. Song, Z. Feng, Y. Li, Y. Ding, Thermal management performances of PCM/water cooling-plate using for lithium-ion battery module based on non-uniform internal heat source, Publisher, City, 2017.

[101] X. Zhang, J. Niu, J.-Y. Wu, Development and characterization of novel and stable silicon nanoparticles-embedded PCM-in-water emulsions for thermal energy storage, Publisher, City, 2019.
[102] A.R. Abdulmunem, Passive cooling by utilizing the combined PCM/aluminum foam matrix to improve solar panels performance: indoor investigation, Publisher, City, 2017.
[103] B. Ding, Z.-H. Qi, C.-S. Mao, L. Gong, X.-L. Liu, Numerical investigation on cooling performance of PCM/cooling plate hybrid system for power battery with variable discharging conditions, Publisher, City, 2020.
[104] J. Cao, Z. Ling, X. Fang, Z. Zhang, Delayed liquid cooling strategy with phase change material to achieve high temperature uniformity of Li-ion battery under high-rate discharge, Publisher, City, 2020.
[105] Y. Zhao, B. Zou, C. Li, Y. Ding, Active cooling based battery thermal management using composite phase change materials, Publisher, City, 2019.
[106] M.R. Salem, M.M. Elsayed, A.A. Abd-Elaziz, K.M. Elshazly, Performance enhancement of the photovoltaic cells using Al2O3/PCM mixture and/or water cooling techniques, Publisher, City, 2019.
[107] S. Mousavi, M. Siavashi, A. Zadehkabir, A new design for hybrid cooling of Li-ion battery pack utilizing PCM and mini channel cold plates, Publisher, City, 2021.
[108] J. Li, H. Zhang, Thermal characteristics of power battery module with composite phase change material and external liquid cooling, Publisher, City, 2020.
[109] D. Li, C. Yang, H. Yang, Experimental and numerical study of a tube-fin cool storage heat exchanger, Publisher, City, 2019.
[110] K.S. Kshetrimayum, Y.-G. Yoon, H.-R. Gye, C.-J. Lee, Preventing heat propagation and thermal runaway in electric vehicle battery modules using integrated PCM and micro-channel plate cooling system, Publisher, City, 2019.
[111] F. Wang, J. Cao, Z. Ling, Z. Zhang, X. Fang, Experimental and simulative investigations on a phase change material nano-emulsion-based liquid cooling thermal management system for a lithium-ion battery pack, Publisher, City, 2020.
[112] J. Cao, M. Luo, X. Fang, Z. Ling, Z. Zhang, Liquid cooling with phase change materials for cylindrical Li-ion batteries: An experimental and numerical study, Publisher, City, 2020.
[113] Q. Li, J.-R. Cho, J. Zhai, Optimization of Thermal Management System with Water and Phase Change Material Cooling for Li-Ion Battery Pack, Publisher, City, 2021.
[114] H. Zhang, X. Wu, Q. Wu, S. Xu, Experimental investigation of thermal performance of large-sized battery module using hybrid PCM and bottom liquid cooling configuration, Publisher, City, 2019.
[115] W. Yang, F. Zhou, H. Zhou, Q. Wang, J. Kong, Thermal performance of cylindrical lithium-ion battery thermal management system integrated with mini-channel liquid cooling and air cooling, Publisher, City, 2020.
[116] W. Zhang, Z. Liang, X. Yin, G. Ling, Avoiding thermal runaway propagation of lithium-ion battery modules by using hybrid phase change material and liquid cooling, Publisher, City, 2021.
[117] Z. Ling, J. Cao, W. Zhang, Z. Zhang, X. Fang, X. Gao, Compact liquid cooling strategy with phase change materials for Li-ion batteries optimized using response surface methodology, Publisher, City, 2018.
[118] D. Kong, R. Peng, P. Ping, J. Du, G. Chen, J. Wen, A novel battery thermal management system coupling with PCM and optimized controllable liquid cooling for different ambient temperatures, Publisher, City, 2020.
[119] M. Kiani, S. Omiddezyani, E. Houshfar, S.R. Miremadi, M. Ashjaee, A. Mahdavi Nejad, Lithium-ion battery thermal management system with Al2O3/AgO/CuO nanofluids and phase change material, Publisher, City, 2020.
[120] G.R. Molaeimanesh, S.M. Mirfallah Nasiry, M. Dahmardeh, Impact of configuration on the performance of a hybrid thermal management system including phase change material and water-cooling channels for Li-ion batteries, Publisher, City, 2020.
[121] Z. Liu, J. Huang, M. Cao, G. Jiang, Q. Yan, J. Hu, Experimental study on the thermal management of batteries based on the coupling of composite phase change materials and liquid cooling, Publisher, City, 2021.

[122] W. contributors, Climate change in The Free Encyclopedia, 2023.
[123] S.A.a.A. Kapoor, Mechanical Design and Packing of Battery Packs for Electrical Vehicles, Publisher, City, 2018.