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Review Article

Thermal management system of e-vehicle Li-ion battery modules: A comprehensive review

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ABSTRACT

Electric vehicles have the potential to address humanity's issues of environmental deterioration and energy scarcity. Electric vehicles frequently use lithium-ion batteries as their power source. The heat is generated when the batteries are subjected to high-power charging and discharging loads. This results in a considerable loss in battery life and raises the possibility of a battery explosion. As a result, quick heat dissipation from the cells is required to ensure safe operation and longer battery life cycles. Air cooling is the most basic type of thermal management; yet, due to its poor thermal conductivity, it has its restrictions. Liquid cooling agents are superior to air cooling systems in terms of thermal control. Liquid cooling, on the other hand, added complexity to the working system, increased operating costs, and increased total system weight. A similar problem might be seen when applying the heat pipe concept of cooling systems. PCM provides several advantages over above mentioned three cooling technologies, but it also has a limited heat storage capacity and poor thermal conductivity. As a result, a hybrid BTMS paradigm emerges. However, research on hybrid techniques is still insufficient. To make effective hybrid BTMS technology, efforts are being undertaken, and earlier research on the hybrid is also summarized in this study.

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INTRODUCTION

Electric vehicles (E-Vehicle, EV) are being used in industry at a rapid rate as a solution to the conventional energy issue due to the sharp rise in power consumption. The management of thermal energy in electric vehicle batteries is a significant concern. Since the introduction of electric vehicles, lithium-ion batteries have been the most sought-after present. Li-ion batteries have taken over the market due to their superior thermal stability, increased energy density, increased power density, and prolonged lifespan. These batteries are suitable for high-drain applications and perform better during rapid charging and discharging. According to studies, operational temperature, which is the primary factor causing battery aging, will have an impact on the performance of Li-ion batteries. Due to polarization, heat produced by reversible chemical reactions, connector resistance, and internal resistance, lithium-ion batteries generate heat. Efficiency in heat removal has turned into a major

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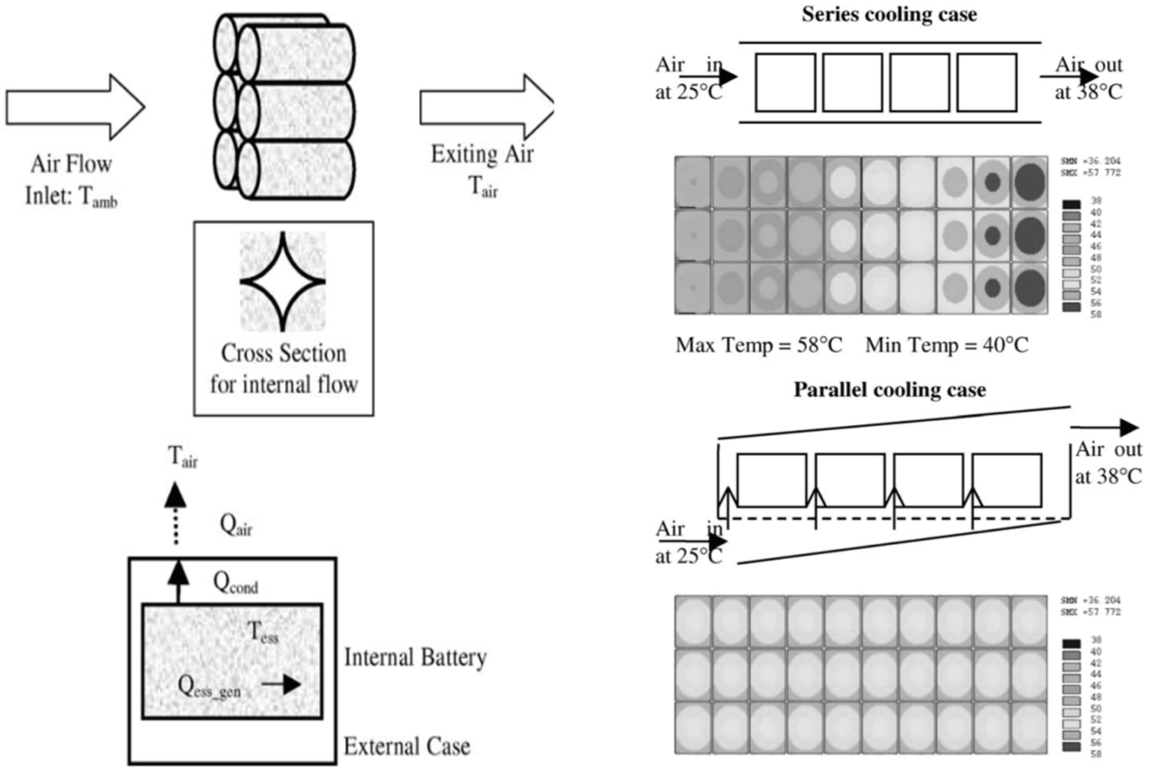


(a) (b)

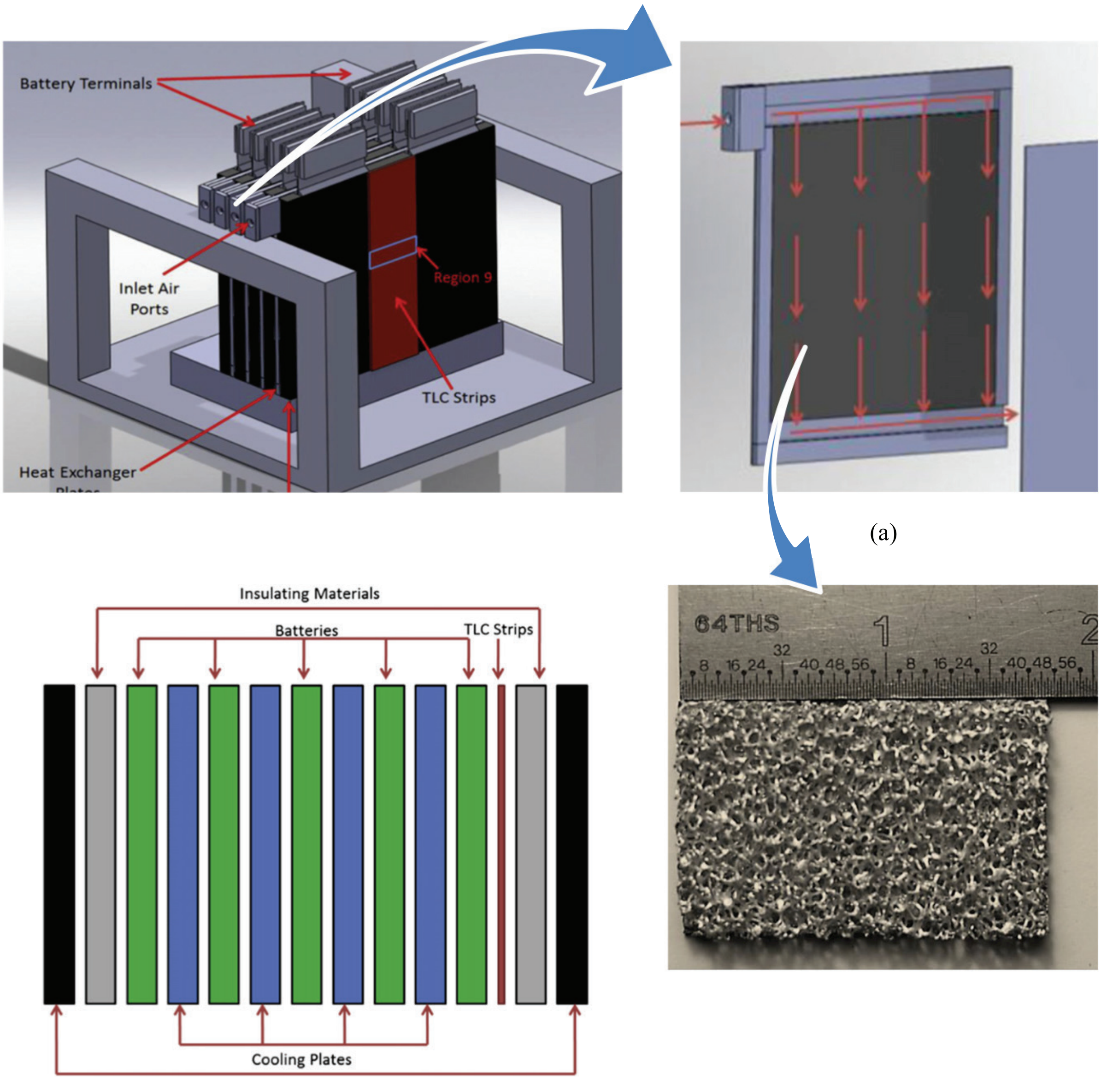
Figure 1. Battery thermal models and results (a) Schematic of the battery model in an advanced vehicle simulator, and (b) two-dimensional analysis of a 30-module battery pack with two types of air cooling (series cooling case and parallel cooling case) [From Pesaran [10], with permission from Elsevier].

issue for the functionality and longevity of Li-ion batteries. Typically, batteries should operate at a temperature between 15°C and 35°C for optimum performance [1]. A battery pack with uniform temperature distribution also has electrically balanced cells. Additionally, it is advised that a battery pack's internal temperature differential not get above 5°C. The ideal operating temperature may vary depending on where you are in the country. The four primary subcategories of battery thermal management technologies are air cooling, liquid cooling, heat pipe, and PCM-based cooling systems. Because air cooling systems frequently fail, they are used for mild temperature control [2]. Liquid cooling has been viewed as the best method because it may have a high thermal conductivity (thermal fluid). However, the intricate configuration of liquid cooling for thermal control required more electricity to power the pump (circulating thermal fluid) [3, 4]. Heat pipe and PCM have lately eclipsed these two cooling methods in terms of thermal management due to their simplicity and their passive mode of cooling. PCM's limited heat conductivity makes it problematic to use it for thermal control. Numerous studies have been conducted to determine whether a PCM can transmit heat more quickly by adding a metal matrix and metal nanoparticles [5-7]. In contrast to conventional cooling systems, the prior study has shown that PCM can give temperature consistency. Water-based cooling systems demand more power than PCM-based cooling systems due to their complexity and overall weight. More research is being done on the hybrid mode cooling system, PCM with heat pipe/liquid cooling/air cooling and is summarized in the following sections.

BATTERY THERMAL MANAGEMENT METHODS

The earliest kind of cooling, air cooling, is still used today due to its benefits, which include its simple design, low energy need, lightweight, low cost of development and maintenance, and environmental friendliness. However, it is advised to choose enough air ventilation for a compact battery module. Thus, the size of its battery pack was enlarged for proper air ventilation. Even though, the battery cell surface temperature could not be maintained uniformly by air cooling. Ultimately, traditional air cooling is currently unable to quickly transfer the heat produced by batteries because of the expanding module capacity and specifications [2, 8-9]. Pesaran [10] examined the air-cooling capabilities of the BTMS. The findings demonstrated that battery temperature could be efficiently lowered by air cooling and maintained at a constant level during low-rate discharge. The comparative study shows that a parallel cooling over a series cooling case could provide uniformity in the cell surface temperature, see Figure 1. Giuliano et al. [11] examined the thermal management system to cool a metal foam-based heat exchanger plate. An open-cell aluminum foam heat exchanger that increases the effective heat transfer coefficient is the most crucial component of the cooling system (Figure 2). Even after 200 A of charge-discharge cycling, the battery's temperature rose just 10°C, and the battery temperature dropped as airflow increased.

Liquid has higher thermal conductivity and heat capacity than air, hence it cools better. Additionally, depending on the type of liquid utilized, liquid can have a variety of qualities. By adding thermal nanoparticles, the liquid can also be heated up more quickly. Using the heat-pipe principle, passive liquid cooling was also researched. Despite having a greater heat dissipation impact, the liquid cooling approach has significant drawbacks, such as a complex system, challenging maintenance, and a high cost [12, 13]. Indirect liquid cooling exhibited the lowest temperature rise and was a better solution than direct liquid cooling, according to Chen et al. [14] (Figure 3).



(a)

(c)

(b)

Figure 2. Solid model of the battery pack with cooling plates inserted between adjacent, (a) exploded view of the assembly, (b) a close-up of 20 PPI, 8% dense aluminum foam cells, and (c) schematic of the cross-section of the entire assembly [From Giuliano et al. [11], with permission from Elsevier].

PCM is used for thermal management as passive cooling to store thermal energy and cool a battery pack. In most cases, the PCM chamber is submerged within the battery pack to store additional heat and there is the possibility of liquid PCM leakage. Zhao et al. [15] say PCM heat dispersion is promising for battery management systems. The cooling efficacies of PCM and the force air-cooling approach were compared by Kizilel et al. [16]. In a passive thermal management system, module cells transmit heat to the PCM matrix, which then conducts it throughout the module. Active cooling, depicted in Figure 4(a), transfers heat from the cells to an airflow maintained between them through natural or artificial convection. Active cooling, on the other hand, as depicted in Figure 4(b), involves the transfer of heat produced within the cells to an airflow that is kept in the space between them through either natural or artificial convection. When PCM cooling is utilized, the temperature in the module returns to nearly ambient levels; see Figure 4(c). In the latter scenario, the heat is promptly absorbed and dispersed by the high thermal conductivity PCM-graphite matrix. These findings suggest that the use of a PCM matrix for cooling can stop the spread of thermal runaway that unintentionally arises (for instance, because of a fault) in a single cell. Consequently, PCM cooling has a competitive advantage over traditional air-cooling of tiny packs.

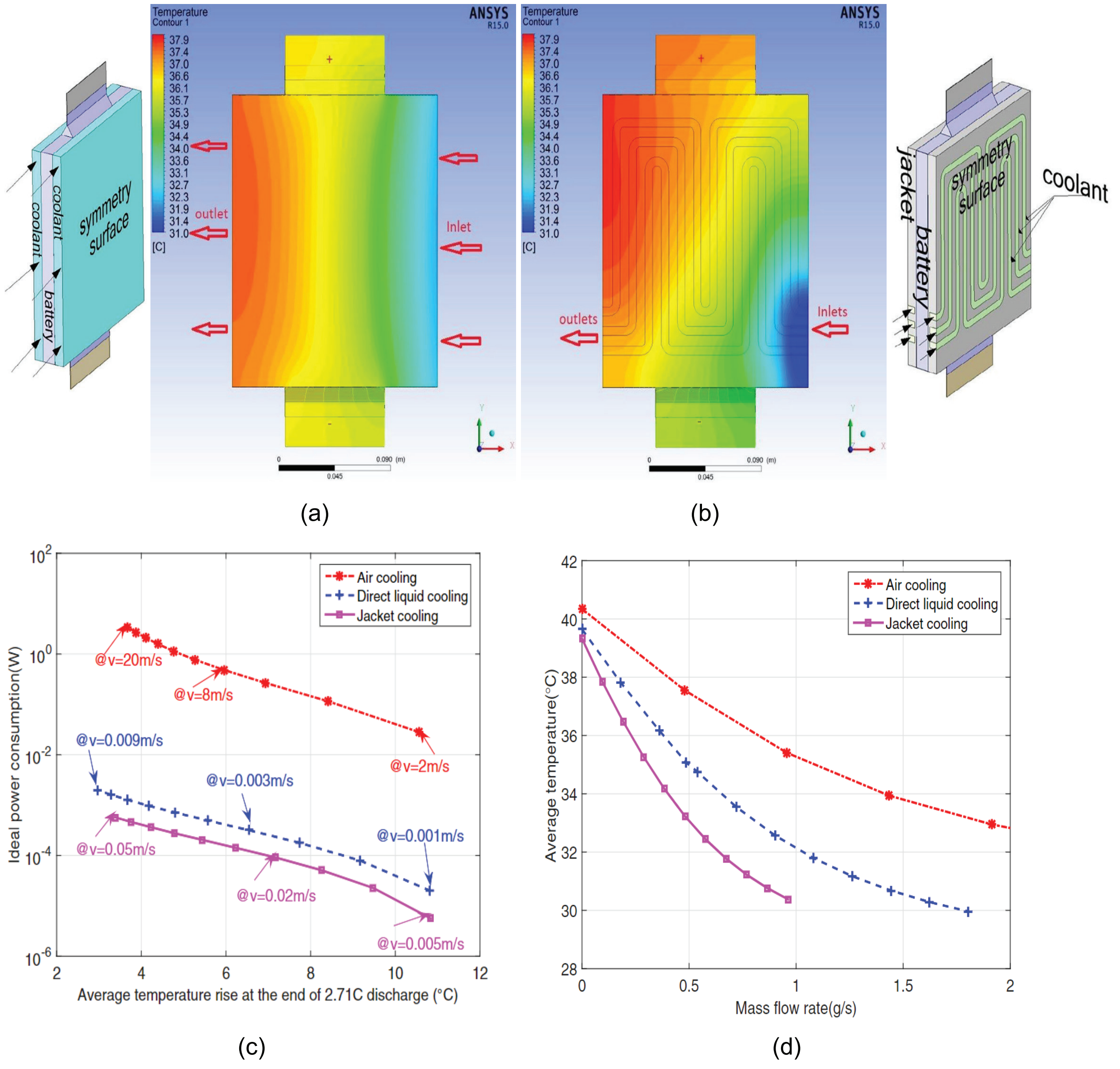
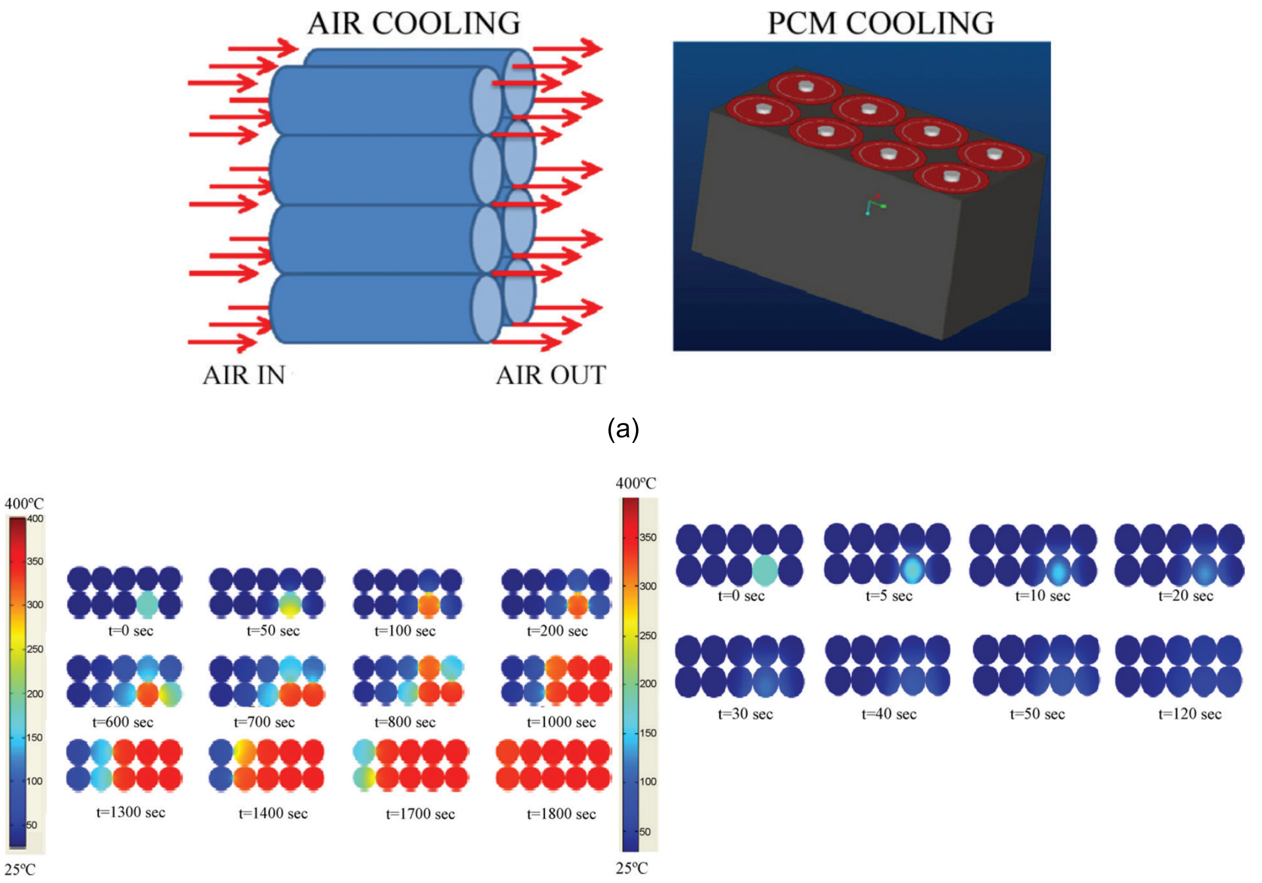


Figure 3. Liquid cooling configuration and results, (a) Temperature distribution of direct cooling, (b) Temperature distribution of indirect cooling(jacket), (c) Ideal power consumption for different cooling methods, and (d) Average temperature at different mass flow rates at the end of 2.71C discharge [From Chen et al. [14], with permission from Elsevier].



(a)

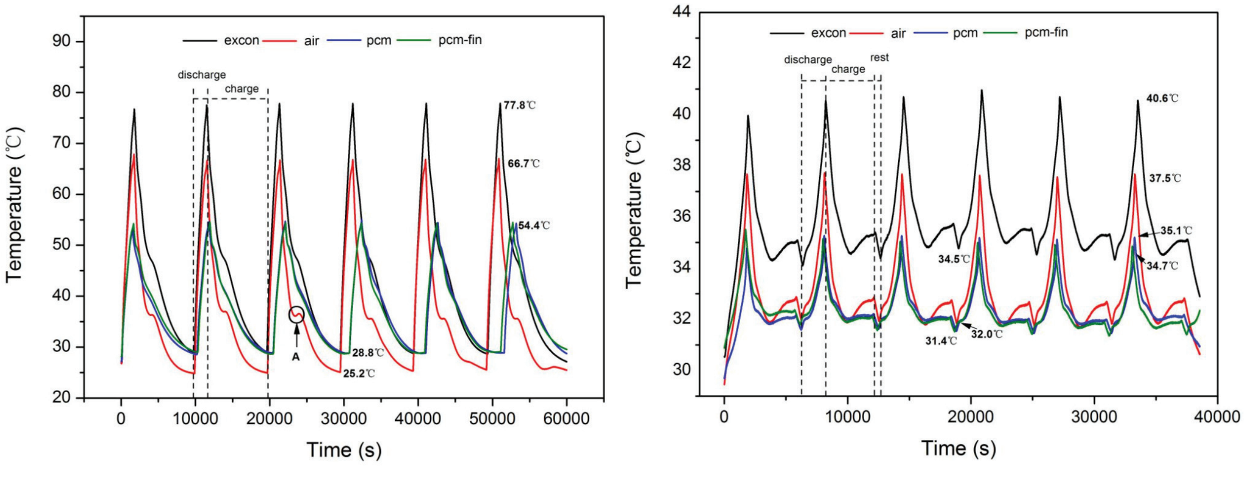
(b)

(c)

Figure 4. Passive PCM thermal management system (a) Representation of active (air) cooling vs. passive (PCM) cooling, (b) Propagation of thermal runaway spreading due to a single runaway cell (light blue at t = 0) in an air-cooled module, and (c)Propagation of thermal runaway due to a single runaway cell is prevented by interstitial PCM microencapsulated in graphite [From Kizilel et al. [16], with permission from Elsevier].

Chen et al. [17] evaluated the thermal performance of Sanyo Li-ion batteries and Sony LiFePO4 batteries using a variety of working conditions, including extreme temperatures, natural convection cooling, PCM cooling, and PCM with fins. As a result, the temperature was effectively lowered and the capacity was maintained throughout the charging and discharging operation, according to the results (Figure 5). Natural convection causes the temperature to stay constant or even increase briefly (area A) throughout the battery charging procedure in Figure 5(a). The LIB's highest temperature in harsh conditions was found to be around 40.6°C, and its minimum temperature when it is shelved after charging was found to be around 35.1°C, see Figure 5(b). The average highest temperature of Sanyo LIB under the PCM cooling is about 54.4°C in the 2 C discharge rate, and it is about 12.3°C decrease compared with the natural convection cooling. A PCM with heat-dissipating fins was advised by Javani et al. [18] to promote heat transmission. Azizi and Sadrameli [13] managed the LiFePO4 battery pack's thermal environment utilizing PCM and aluminum mesh composites. PCM and aluminum wire mesh reduced battery surface temperatures and improved battery pack operation.

There is no perfect solution for PCMs used in battery thermal management, regardless of their use in combination with heat dissipation fins or metal mesh. The PCM and heat dissipation fins/metal mesh will cause an increase in the weight of the BTMS device. Nayak et al. [19] examined the efficiency of these enhancers/additives to boost PCM's thermal conductivity in BTMS. Two different types of thermal conductivity enhancers (TCE) systems were examined. In one arrangement, a highly porous TCE matrix is uniformly dispersed throughout the PCM, while in the other, TCE is arranged as fins that extend from the base (a heat sink), with PCM filling the remaining space. The results demonstrate that using TCE material in fins form increases heat sink performance. Additionally, it was found that rod-type fins outperform plate-type fins in terms of performance.



(a) (b)

Figure 5. The temperature changes of (a) Sanyo Li-ion battery, and (b) LiFePO4 battery during charging and discharging [From Chen et al. [17], with permission from MDPI].

According to Javani et al. [18] investigation on the effects of a PCM on Li-ion batteries, it may be able to balance out the temperature distribution and keep the battery within a specified temperature range. Weng et al. [20] investigated the impact of numerous specific parameters of PCMs and concluded that PCM modules with a thickness of less than 10 mm had the best cooling capabilities. When a 3 mm thick PCM was placed around the cell, the temperature distribution improved by about 10% and the 12 mm thick PCM reduced the temperature to 3.04°C [21]. However, when absorbing a lot of heat in practice, PCM is prone to heat saturation. High-power batteries cannot be thermally managed with pure PCM for an extended period. Thus, PCM is embedded with high thermal conductivity materials, such as expanded graphite, carbon fiber, graphene, aluminum foam, copper foam, and other materials, to improve the thermal conductivity of PCM [5-7,16]. Zhang et al. [22] created a method to regulate temperature rise by using paraffin as a source of heat dissipation and to boost the thermal conductivity of PCM using expanded graphite (EG). In their investigation, a paraffin-EG composite PCM was generated and characterized (Figure 6(a-c). Figure 6(d) shows the maximum temperature curves for cooling modules that use PCMs, and air cooling is compared and was observed that a pure air-cooling module's maximum temperature is 56.8° C and tends to rise swiftly. The black curve demonstrates a maximum temperature reduction of 57.7% and a maximum temperature of 36°C that may be achieved with the PCM cooling module. Thus, PCM cooling of the battery module helps improve thermal management. According to tests, the PCM cooling system can balance temperature differences to within 5°C and keep the peak temperature under 42° C. Peak temperature can be adjusted within 50°C, even in systems with high discharge pulse currents.

Hussain et al. [23] used a composite to research heat control techniques for highly powerful lithium-ion batteries (nickel foam-paraffin wax), Figure 7(a-c). Figure 7(d-e) shows how the temperature changes over time for pure paraffin and when using a nickel foam-paraffin composite at the same discharge rate (0.5 C). Under a 2 C discharge rate, nickel foam-paraffin composite reduces surface temperature by 31% and 24% compared to pure PCM and natural air convection, respectively. Additionally, it has been noted that surface temperature decreases as porosity and pore density rise. Similar findings were made by Mohammadian et al. [24], who found that decreasing the porosity of the porous design lowers the maximum temperature inside the battery. Joshi and Rathod [25] also studied the use of PCM with metal foam and found that significantly improves melting performance. In this work, optimal thermal conductivity enhancement is attempted introduced by the local installation of metal foam near high-temperature gradient regions. Baby and Balaji [26] experimentally investigated the impact of copper porous matrix-filled PCM used in heat sinks. The impact of orientation is also investigated by creating a tracking system that can position the sink in any orientation. Dinesh and Bhattacharya [27] examined pore size's effect on PCM-metal foam energy storage. Small pore size melts faster and increases heat transfer in all porosity systems. Jilte et al. [28] studied a novel modified battery module configuration using nano-enhanced PCM for its thermal management system.

In addition, many research employs heat pipe thermal control techniques. Ye et al. [29] examined the thermal performance of the heat pipe thermal management system (HPTMS) in steady state and transient conditions using a numerical model. Experiments and transient simulations show that the enhanced HPTMS can thermally regulate batteries during fast charging. The air-cooled HPTMS is

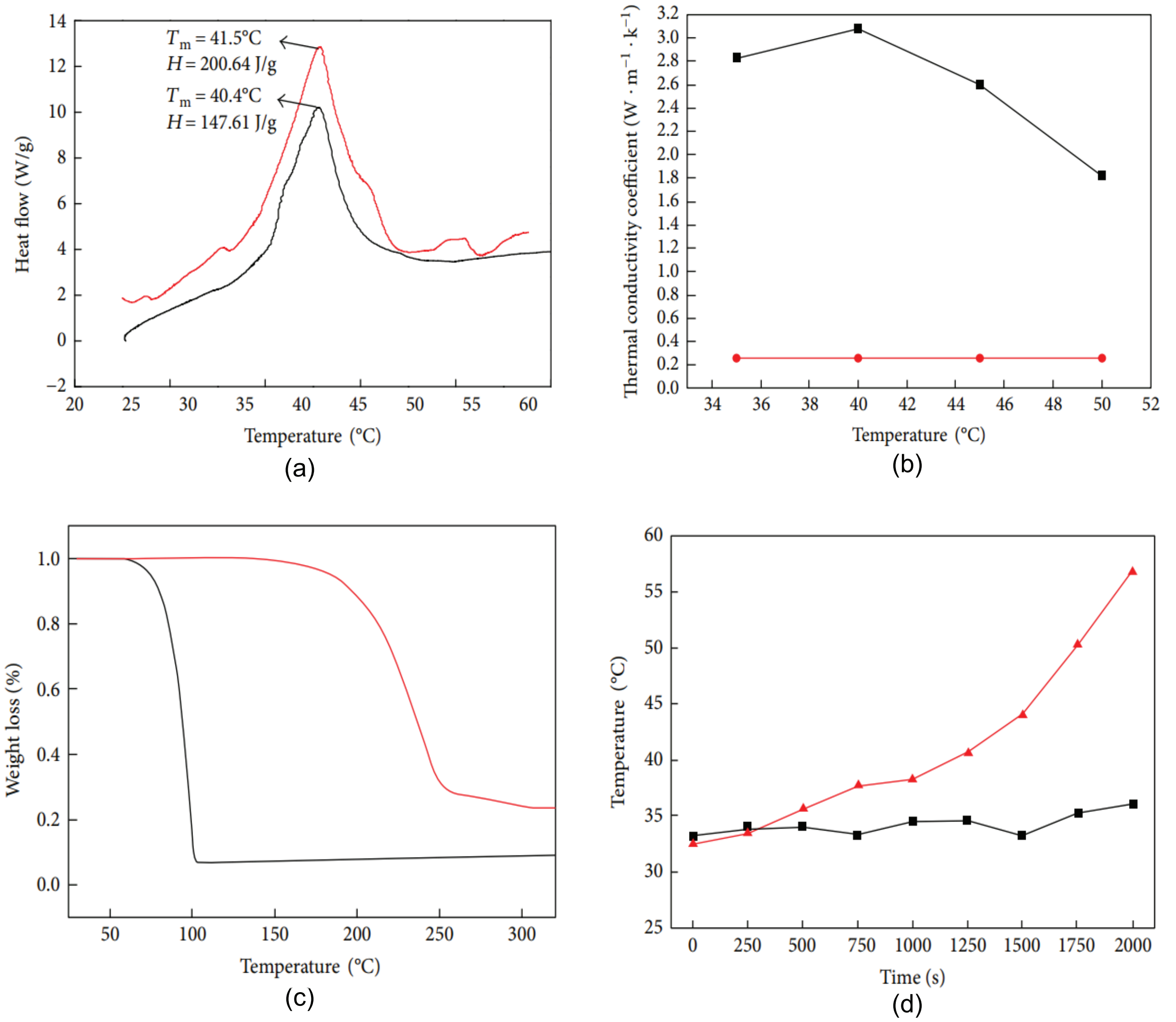


Figure 6. Characterization of Paraffin/Expanded Graphite Composite PCM, (a) latent heat between pure PA and PA/EG composite PCM, (b) thermal conductivity between pure PA and PA/EG composite PCM, (c) mass changing trend with the temperature between pure PA and PA/EG composite PCM, and (d) The Tmax comparison of test data between the air cooling module and PCM cooling module [From Zhang et al. [22], with permission from Wiley].

unsuitable for fast-charging battery thermal management due to its low specific heat capacity. The enhanced design with prismatic cells is next empirically assessed at the level of the battery pack and the individual unit. The findings demonstrate that lithium-ion battery packs can be quickly charged using a redesigned heat pipe thermal management system [30]. Putra et al. [31] evaluated the efficiency of a Flat plate loop heat pipe (FPLHP) as a heat exchanger in the thermal control system of a lithium-ion battery. Stainless steel mesh was used as a capillary wick. Acetone, alcohol, and distilled water made up the working fluids, which accounted for 60% of the entire mixture. With an evaporator temperature of 50°C and thermal resistance of 0.22 W/°C at 1.61 W/cm2, acetone performed best. Liang et al. [32] developed combined heat transfer, multi-cell, and heat pipe sub-models for a heat pipe-cooled serially connected battery module. Even as the coolant temperature drops, the module’s temperature difference rises. When coolant temperature is decreased by 10°C at a 5C discharge rate, battery module voltage and usable capacity are lowered by 0.88 to 1.17 percent. Dan et al. [33] developed a thermal management system using a small heat pipe array (MHPA). The suggested model’s accuracy is proven by comparing simulation results with steady-state, dynamic, and operating data. The simulation results demonstrate that under rapidly changing operating conditions, the thermal management system for MHPA-based batteries reacts swiftly to preserve temperature stability. Wang et al. [34] propose the use of heat pipes for a battery module with cylindrical cells. The circumferential angle between the conduction

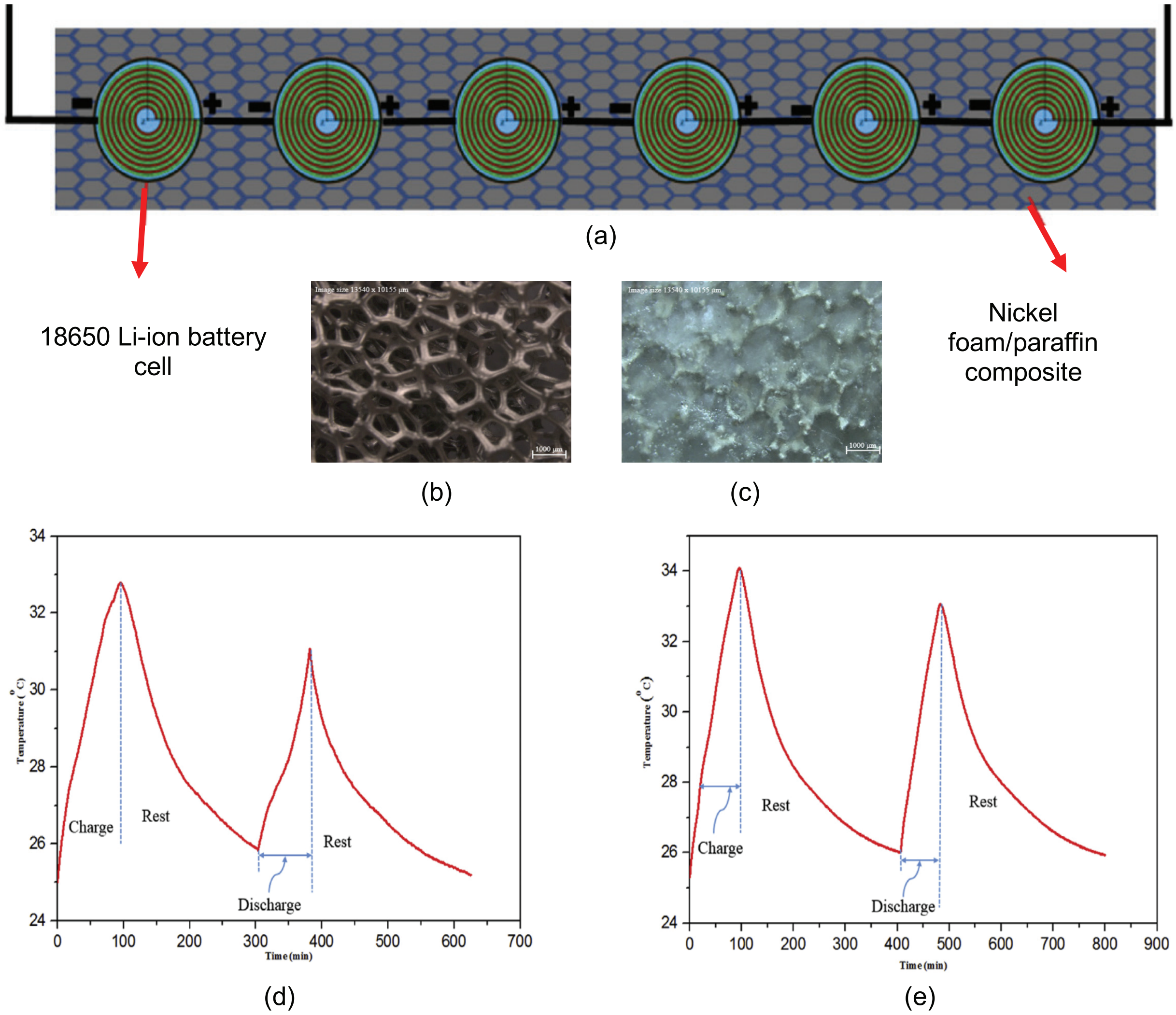


Figure 7. Configuration of Nickel foam/paraffin wax and results, (a)Schematic diagram of battery pack surrounded by nickel foam-paraffin composite, (b) Images of nickel foam, (c) paraffin/nickel foam composite (d) Temperature response with time using pure paraffin as a cooling medium under 0.5 C discharge rate, and (e) Temperature response with time using nickel foam-paraffin composite as a cooling medium under 0.5 C discharge rate [From Hussain et al. [23], with permission from Elsevier].

element and battery spacing has a greater impact on the maximum temperature and temperature difference of the battery module. Behi et al. [35] propose a hybrid thermal management system for electric vehicles that combines heat piping and air cooling. When compared to natural air conditioning, these systems can reduce module temperatures by 34.5, 42.1, and 42.7 percent, respectively. Using heat pipe copper sheets (HPCS), heat pipes, and forced air cooling, battery module temperature uniformity increased by 39.2%, 66.52%, and 73.433%, respectively. More research has led to the recommendation of a sandwiched heat pipes cooling system (SHCS) for lithium-titanate battery cells. For natural convection, the maximum cell temperature embedded with SCHS is 49°C, for SHCS alone it is 38°C, and for forced convection, it is 37°C [36]. Gan et al. [37] proposed heat pipe-based thermal management for cylindrical battery cells. Compared to natural cooling, a 5 C discharge rate reduces battery temperature by 14 °C. Jin et al. [38] used modeling to analyze board-and-pipe BTMS heat performance. The study found that heat pipes and composite boards produce greater heat. Moreover, by employing a combination of vertical and horizontal pipes, achieving superior overall cooling efficiency of BTMS than single pipes. The optimal arrays significantly enhance the comprehensive performance of the traditional composite board Thermal Management System (TMS). Following a complete charging/discharging cycle at a 3C rate, T_{max} and ΔT reach 296.85 K and 3.29 K, respectively. Furthermore, the cooling capabilities are notably impacted by the contact area between the battery and the pack shell. Ren et al.

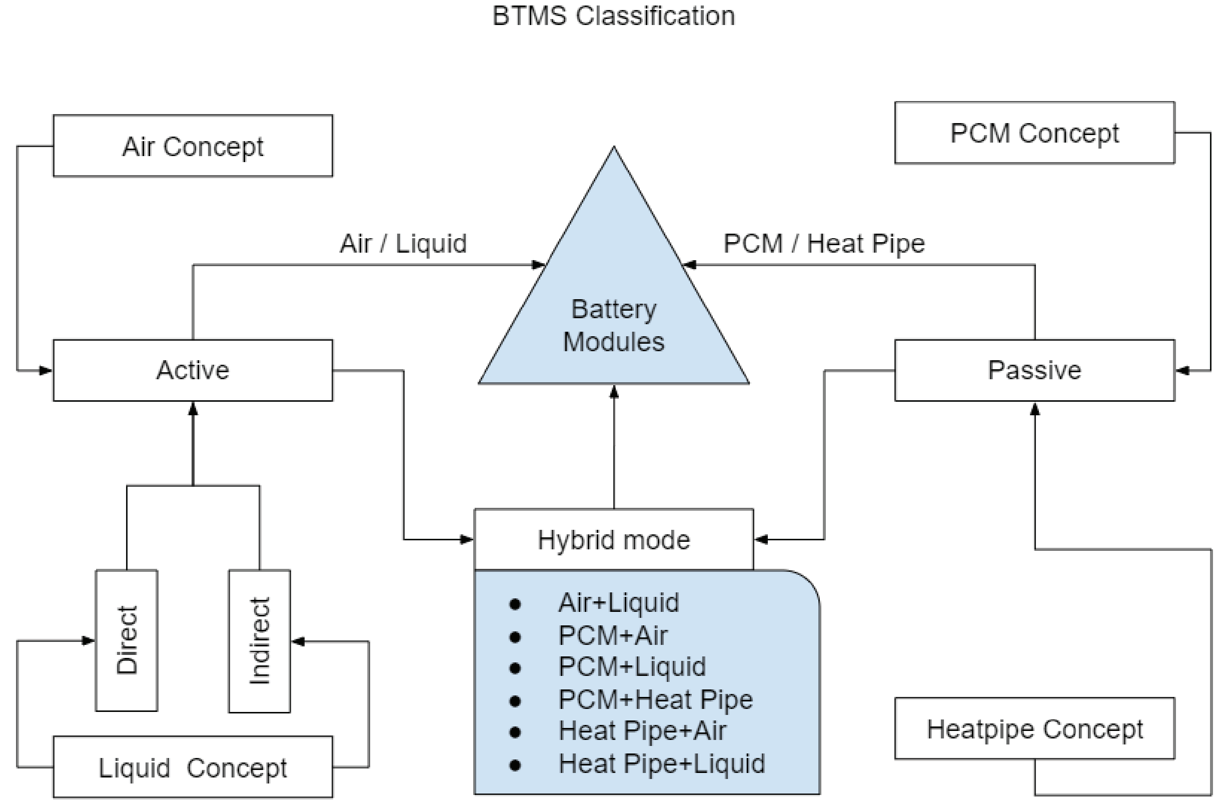


Figure 8. Basic classification of Battery thermal management system (BTMS) based on cooling concept techniques.

Table 1. Advanced in liquid cooling system

Sl. No.	Authors	Abstract	Observation
1	Wei andAgelin-Chaab [47]	Studied hybrid cooling concept based on a simple air-cooling duct that cools by convection. The study compares battery heat behavior under hybrid, air, water, and no cooling.	The hybrid cooling showed a much greater potential for battery packs with higher energy and power density. The hybrid cooling system was able to decrease the maximum average surface temperature from 55°C to 30.5°C (no-cooling case). However, the air-cooling and the water-cooling decreased the temperature to 44°C and 38°C compared to the no-cooling case. That the hybrid cooling method has a much higher cooling efficiency than both convective air cooling and the water-cooling method, because of the latent heat extracted by the water vaporization.
2	Saw et al. [48, 49]	Mist cooling of lithium-ion batteries was studied. Experiments and numerical simulations are conducted to investigate the thermal performance of conventional dry-air cooling and mist cooling. Investigations have compared dry air cooling to mist cooling using numerical calculations and experimental.	Mist cooling can offer lower and more uniform temperature distribution compared to dry air cooling. It provides an excellent cooling performance to maintain the batteries temperature within optimum operating temperature range and can minimize the variation of temperature across the battery module. Also, improvement in overall heat transfer performance have seen in the downstream.
3	Yang et al. [50]	Air pre-cooling by water spray evaporation is applied to the battery pack thermal management. The influences of water flow rate, water droplet size, air velocity and ambient temperature on the battery performance are investigated by computational fluid dynamics.	The water spray cooling greatly reduces the maximum temperature but increases the temperature difference compared to dry cooling. A high-water flow rate leads to the reduced maximum temperature but plays the adverse role in the maximum temperature difference.

Table 1. Advanced in liquid cooling system (continued)

Sl. No.	Authors	Abstract	Observation
4	Huang et al. [51]	Spray cooling is used to prevent battery thermal runaway, and the inhibitory impact of spray cooling on the battery is investigated through a series of experiments. The effect of the spray trigger temperature (T_e) and the spray duration (t_s) on the suppression of thermal runaway was investigated in this experiment.	This has been identified that t_s should be selected according to T_e. When T_e is high, the t_s should be appropriately extended to ensure that thermal runaway will not occur after spraying ends. Choosing a suitable t_s can effectively reduce the working fluid consumed and improve economic efficiency whilst ensuring thermal safety.
5	Liu et al. [52]	Water mist was proposed and investigated through a series of experiments to prevent thermal runaway in lithium-ion batteries.	Water mist exhibited excellent cooling capacity and Thermal runaway propagation in the battery module easily prevented. The cooling mechanism primarily relied on the latent heat of water mist evaporation, resulting in a cooling power of 40.71 W for an individual battery.
6	Behi et al. [53]	Heat pipe-based air-cooling system is built to control the temperature of the lithium-ion (Li-ion) cell/module in the high current (184 A) discharging rate. The experimental and numerical assessment of cell/module temperature considers the absence of natural convection, forced convection, and evaporative cooling.	Heat pipe-based air-cooling system found that the average cell temperature reached from 54.3°C to 35.9°C, which showed a 33.7% reduction. Evaporative cooling enhanced the cooling system by reducing cell temperature by 35.8% and module temperature by 23.8%.
7	Shahid et al. [54]	Battery thermal management of cylindrical lithium-ion cells for electric vehicles with hybrid concepts combining air and liquid cooling are examined using numerical simulation. Here, concept includes vortex generators and jet inlets to increase turbulence within the battery pack, and further evaporative cooling is achieved through fiber channels saturated by a reservoir located beneath the battery pack, facilitated by capillary action.	Results of the evaporative cooling concept indicated a significant improvement in the cooling at the pack level. Also reduces complexity of the multiple air-cooling passive methods employed not only address safety concerns arising from liquid leakage within the battery pack but also eliminate the associated safety issues.
8	Wu et al. [55]	The impact of spray cooling on the thermal control of the battery system at high discharge rates was examined.	For the spray cooling, a greater degree of temperature consistency was seen across the battery pack. It was observed that the spray cooling can provide a lower temperature rise and a more uniform temperature distribution for the battery module, and battery module temperature variations were all under 5°C.
9	Wang et al. [56]	Innovative lithium-ion pouch battery thermal management system (BTMS) with small footprint and superior heat dissipation was invented. Five 10Ah lithium-ion pouch batteries were used to test the cooling performance of liquid-immersed BTMS.	A liquid-immersed cooling strategy with a 13.2 cm immersion depth and 0.8 L/min flow rate at 2C (100A) and 25°C showed the best thermal management performance. The highest temperature differential of the battery module dropped from 4.97°C to 1.23°C when compared to without immersion coolant (natural air cooling).
10	Jang et al. [57]	Studied the thermal performance of a novel liquid cooling system for Li-ion batteries with heat pipes under various operating conditions and design factors.	In comparison to the liquid cooling, Liquid cooling with heat-pipe shows a much higher performance and owing to the increased heat transfer area. The maximum temperature of the battery module decreases by 6.1°C and 9.4°C under the basic and optimized conditions relative to those in the liquid cooling, respectively.

Table 2. Advanced in PCM cooling system

Sl. No.	Authors	Abstract	Observation
1	Hekmat and Molaeimanesh [58]	Investigations were conducted on two-hybrid cooling systems that included a PCM and a water-cooling circulation pipe.	The results indicate that PCM maintains uniform temperature distribution among cells. However, the passive cooling scenario took a longer time to bring the cells to the average temperature of 30°C compared to the two hybrid cases. Additionally, the maximum temperature in the hybrid cases was noticeably lower.
2	Behi et al. [59]	Hybrid battery thermal management for cooling the battery module, using phase change material (PCM) and liquid cooling, has been experimentally studied. The thermal behavior of the battery module consisting of 30 cells has been considered by different cooling scenarios. Three scenarios comprising natural convection, PCM heat buffer plate, and hybrid cooling have been investigated experimentally.	The module temperature exceeds the safe temperature range using natural convection. The PCM heat buffer plate performs an acceptable cooling efficiency as a passive cooling system. The hybrid cooling system demonstrates a well-balanced design with active and passive cooling systems which provide temperature reduction for the charging and discharging process respectively.
3	Bamdezh et al. [60]	Hybrid thermal management using cooling water channels (as the active cooling) and a composite of paraffin PCM and Al foam surrounding each lithium 18650 cylindrical cell (as the passive cooling) is investigated.	The evaluation of the results demonstrates that increasing the axial and radial conductivities have a negligible effect on the time evolutions of average cell temperature and liquid fraction, while increasing the tangential conductivity enhances the heat transfer, and consequently leads to better controlling average cell temperature and faster PCM solidification process. Further, increasing the axial thermal conductivity has a positive effect on controlling the maximum temperature difference through the cell.
4	Hekmat et al.[61]	Hybrid BTMS including PCM, and liquid cooling channels performance in comparison with numerical investigations are conducted on various BTMSs with similar characteristics, exploring different discharging rates and varying coolant flow rates.	Results show that for discharging rate of 2C, the maximum temperature difference between the cells is 2.8°C for the passive BTMS.
5	Singh et al. [62]	Numerical study was carried out to examine the performance of a hybrid air- PCM cooled lithium-ion battery module at various air inflow velocity (0–0.1 m/s) and different thickness of PCM encapsulation (1–3 mm) for 1C, 2C and 5C discharge rates. Commercial SONY 18650 cells (25 nos.) were placed in a square box with two different cell arrangements, namely, square and diamond.	The highest temperature decreased without PCM by around 20 K when velocity varied from 0 to 0.1 m/s. When a thin PCM layer of thickness t = 1 mm is employed over the cells, the cell temperature drops dramatically and shows the maximum drop of ~30 K at 1C and ~45 K at 5C. At low discharge rate and high air velocity, the diamond cell arrangement shows better cooling performance than square cell arrangement and may reduce the battery temperature by ~3–4 K without PCM.
6	Wang et al. [63]	BTMS is proposed and evaluated from the economic and engineering perspectives. Numerical models are compared with PCM. Further, the suggested hybrid cooling system's thermal performance at the pack level is investigated considering cell-to-cell variation.	Results shows that for a 53 Ah lithium-ion battery under a 5C discharge rate, a hybrid cooling system with two-sided cold plates can reduce the maximum temperature from ∞64°C to 46.3°C.
7	Zhou et al. [64]	A series of experiments are conducted to systematically investigate the cooling efficiency of PCM and the several detailed factors on the thermal management performance, such as the structure, phase change temperature and thickness of PCM	The results show that the PCM structure (sides of the battery surround by PCM) has an excellent heat dissipation efficiency at a high discharge rate of 2C. Increasing the thickness of PCM enhances the cool performance, but the heat dissipation efficiency will decrease once the thickness exceeds the value of 25 mm. Furthermore, it is found that the PCM structure with 25 mm thickness can keep the maximum temperature of the battery under 55 C in dynamic cycling.

Table 2. Advanced in PCM cooling system (continued)

Sl. No.	Authors	Abstract	Observation
8	Lee et al. [65]	A battery thermal model and two-phase PCM simulation model were developed and validated through experimental data, and a parametric study was conducted by changing the parameters of the PCM and operating conditions of the liquid cooling system.	In the suggested system, the battery module reached 38.4 °C and changed 3.9°C, over a charge-discharge cycle. The thickness of 2 mm is selected as an appropriate value because PCM in the upper part did not become a completely liquid state immediately after 3C charging.
9	Xin et al. [66]	A hybrid cooling system made of composite phase change material (RT44HC/expanded graphite) and counterflow liquid cooling is developed to improve the thermal performance of a battery module with 25 cylindrical batteries at 40°C and 5C discharge rate.	The results show that the optimal mass fraction of expanded graphite is determined to be 12%, aligning with constraints on both maximum temperature of 45.25°C and temperature difference of 3.49°C. In addition, compared with the parallel flow direction, the counterflow flow direction scheme possesses better thermal performance.
10	He et al. [67]	Studied pulsed-power source (PPS) to enhance shale oil extraction when paraffin and low melting temperature alloy (LMTA) are used as PCMs. For external heat shielding, silica aerogels, glass wool, and phenolic foam are employed.	The findings indicate that the LMTA can prolong the safe operating duration of equipment, increasing it from 50 minutes to over 250 minutes when compared to paraffin. Simultaneously, it reduces the average equivalent thermal resistance from 1.7 K/W to approximately 1.1 K/W. Furthermore, the incorporation of glass wool and phenolic foam is effective in extending the operating time by 63% and 57%, respectively, particularly with an external ambient temperature of 100°C.
11	Peng et al. [68]	The PCM process and its effect on battery thermal behaviour are quantitatively evaluated for different C-rate discharge processes (0.5C, 1C, 2C), PCM characteristics (different mass fractions of expandable graphite), and charge-discharge cycles of the battery module.	The results indicate that the PCM liquid fraction distribution is not uniform during the discharge process, the PCM starts to melt from its outermost neighboring the batteries and its upper part gets more liquid due to natural advection of liquid PCM. A tested composite PCM containing 12 wt% expanded graphite (EG) exhibits superior heat dissipation performance compared to pure PCM. As a result, it is more suitable for BTMSs.
12	Zhang et al. [69]	A unique approach of placing integrated fins on and between cooling channels in PCM was presented to lighten and simplify battery pack structure and prevent uneven liquefaction of PCM and liquid cooling.	The results showed that the introduction of liquid cooling could effectively reduce the maximum temperature of the battery pack, but the maximum temperature difference of the battery pack would increase slightly. It showed that the reasonable arrangement of fins on the liquid cooling channels could reduce the maximum temperature of the battery pack and improve the temperature uniformity of the battery pack.
13	Ambekar et al. [70]	Combination of PCM and fins as a thermal conductivity enhancer (TCE) for battery modules are presented. To determine the best layout for efficient heat transmission from the system to the borders and subsequent convection to the environment, internal fin configurations are constructed and assessed.	The results show a more uniform distribution of temperature within the battery module, leading to better thermal performance over a longer operating time. Even after 2.5 cycles of 2C and 3C discharge rates, the PCM-integrated fins maintain the battery module temperature below 60 °C.
14	Liu et al. [71]	Hybrid system that couples PCM/copper foam with helical liquid channels is proposed and the effects of the influencing factors are investigated numerically	The hybrid system reduced the temperature 30 K more than natural convection. Increasing helix diameter and tube number lowered battery temperature but increased power consumption. In terms of the copper foam parameters, the porosity has an optimal value of 0.92 for the studied system while the battery temperature continuously decreases with the increasing pore density.

Table 2. Advanced in PCM cooling system (continued)

Sl. No.	Authors	Abstract	Observation
15	Chen et al. [72]	Examines the effectiveness of a BTMS employing a PCM and a heat pipe (HP). The performance of the BTMS is compared to that of the one with solely HP, find that PCM can effectively reduce the temperature difference in battery pack. Then, the influences of the environmental parameters, the parameters of the HP and PCM on system performance are investigated using numerical methods.	Increasing convective heat transfer coefficient (h), latent heat, and PCM thickness, or decreasing ambient temperature, reduces battery pack maximum temperature while increasing temperature disparity. Enhancing the equivalent thermal conductivity of started HP (kHP-S) and lowering the starting temperature can enhance the heat dissipation of the battery pack. When the melting temperature of PCM is below the starting temperature HP, it results in a significant temperature difference in the battery pack. Optimized results imply PCM thickness distribution can boost system performance.
16	Zhang et al. [73]	Heat pipe assisted separation type BTMS using porous metal foam saturated with PCM is developed. The performance of the BTMS is experimentally investigated using a Lab-scale battery pack with constant current discharge rates of 1C, 3C, 4C, 5C, as well as different discharge-charge cycles.	The results show that the proposed system offers a more suitable temperature and can better reduce the temperature imbalance within the battery pack than other methods. Especially, under the long-time operation conditions, the reliability and performance of the proposed BTMS can be greatly improved.
17	Wu et al. [74]	Hybrid cooling for a battery module is demonstrated over the single liquid cooling and the encapsulant cases, and then a structural optimization for the hybrid cooling system is conducted based on the response surface methodology (RSM) and numerical modeling.	Compared with the single liquid cooling case without PCM, the maximum temperature and temperature difference of the present hybrid cooling system (baseline case) are reduced by about 42.67% and 38.27%, respectively.
18	Safdari et al.[75]	Hybrid BTMS configurations are studied, using PCM as passive and air coolant as active cooling system. The PCM that encloses the battery cell is made up of three different vessel cross-sections with similar volumes: round, rectangular, and hexagonal. The same pack holder and 12 Sony 18650 batteries are used in these BTMS.	Results reveal that the thermal performance of both hexagonal and circular PCM vessels show generally the same behavior. It was found that the circular PCM configuration is the best one. However, in the high rate of charging or discharging condition, the uniform air channel around the rectangular shape makes a more efficient cooling.
19	Mashayekhi et al [76]	In this study, a new BTMS integrating active and passive approaches is used to explore the thermal response of lithium-ion batteries at high discharge rates. The BTMS's passive component was refined paraffin in blockform (P 42-44 #107150) mixed with porous copper metal foam, while the component's active component was an aluminum mini-channel carrying coolant flow.	Results showed that passive cooling was inefficient in keeping the battery temperature below the safety limit of 60°C in high discharge rates. The hybrid BTMS reduced the steady-state temperature of batteries by 19.5% compared to active method at a Reynolds number of 340 and heat generation power of 3.7 W. It was shown that, compared to the base case with water flow, nanofluid can reduce the maximum temperature of batteries by 15.5% and 8.5% in active and hybrid methods, respectively.
20	Song et al. [77]	The thermal performance of the conjugated thermal management system with both PCM and liquid cooling was numerically evaluated to address the challenging thermal problem for battery modules operating continuously under high charge/discharge rates.	Conjugated cooling can significantly slow down the battery temperature rise rate in comparison with the pure PCM cooling for the high battery heating power. Compared with the single liquid cooling, the battery temperature can be significantly lowered during the melting process of the PCM by the conjugated cooling due to the latent heat of the PCM.
21	Huang et al. [78]	A serials PCM based BTMS for cylindrical lithium battery module were designed, which were pure PCM, heat pipe coupled with air assisted PCM (PCM/HP-Air), heat pipe coupled with liquid assisted PCM (PCM/HP-Liquid), respectively.	The results by experiments at different discharge rates indicated that heat pipe balancing the temperature uniformly for PCM based battery module. The heat pipe coupled with liquid cooling shows highest temperature could be maintained at 50°C during 3 C discharge rate.

Table 2. Advanced in PCM cooling system (continued)

Sl. No.	Authors	Abstract	Observation
22	Zhao et al. [15]	An PCM/HP coupled BTM module was designed and tested experimentally to understand the performance for cylindrical power battery.	The results showed that the effect of temperature control based on PCM is improved comparing to air based BTM under natural convection. The maximum temperature of PCM/HP coupled BTM can be controlled below 50°C for longer time than those of the air-based case and PCM-based case under the same conditions.
23	Jiang et al. [79]	A tube-shell Li-ion battery pack with a passive thermal management system (TMS) using composite phase change material (PCM) was developed. The battery pack consisted of expanded graphite (EG)/ paraffin composite, aluminium tubes, baffles, and a shell.	EG/paraffin composite significantly reduces cells temperature rising and keeps the maximum temperature difference across the battery module within a low value under 2°C. The tube-shell battery pack with EG/PCM exhibits high heat dissipation efficiency during cooling process.
24	Bai et al. [80]	The battery module with PCM/ water cooling-plate was designed and numerically analysed based on the energy conservation and fluid dynamics. Factors such as height of water cooling-plate, space between adjacent batteries, inlet mass flow rate, flow direction, thermal conductivity, and melting point of PCM were analyzing their respective impacts on the cooling performance of the module.	The PCM/water cooling plate provided good cooling efficiency in controlling the lithium-ion battery module temperature. And the 5 cm high cooling plate made the best cooling performance. As the space between adjacent batteries increased, the maximum temperature showed little change, but the temperature field got more uniform.
25	Wu et al. [81]	Heat pipe assisted PCM based BTMS is designed to be compact and efficient from the point of practical application. Maximum temperature rises and temperature distribution within the battery module were experimentally studied under different discharge rates.	The highest temperature can be controlled under 50°C as forced air convention is used to enhance the heat transfer coefficient. But the effectiveness of further increasing air velocity is limited when the velocity reaches a critical value during the phase transition process of PCM. For the use of PCM and HP, significant reduction in temperature is observed compared with no cooling strategy especially during high discharge rates.

[39] developed an active air conditioning TMS based on a U-shaped micro heat pipe array (MHPA) to mitigate battery temperature rise and enhance temperature uniformity in the battery module during charge and discharge cycles. U-shaped MHPA modules, specifically Active Air Cooling with U-shaped (AAC-MHPA) and Passive Air Cooling with No U-shaped (PAC-NMHPA), achieve a temperature of 51.70°C and 57.83°C with 2C constant charge and discharge for comparison purposes. Alihosseini and Shafaee [40] study a heat-pipe-equipped lithium-ion battery heat management system. The experimental results show that although battery surface temperature rises when ambient temperature rises, this effect may be regulated and used as an active strategy due to the heat pipe's decreased thermal resistance. Forced convection in the condenser portion can also uniformly disperse battery surface temperature below 40°C. Jouhara et al. [41] evaluated a heat pipe-based thermal control technique for batteries. Results show that heat pipe absorbed cell heat and transferred it to water or a refrigerant for external cooling. Lei et al. [42] designed a sintered copper-powder heat pipe combined with water spray. The results demonstrate the proposed BTM system is highly effective. In the case of Id = 24 A, the maximum temperature and maximum temperature difference of the battery surface are dropped by 29.2°Cand 8.0°C in comparison to those without BTM aids. Ren et al. [43] suggest preheating LIB TMS with a U-shaped MHPA. U-shaped MHPA-based TMS heats from 20°C to 0°C in 26 minutes. Yao et al. [44] present a heat pipe-and-refrigerant battery module and show that the battery module's maximum temperature may be regulated at predetermined temperatures (25°C, 30°C, and 35°C), and the temperature differential between battery cells can be kept under 3°C.

In the recent research approach towards battery thermal management, hybrid modes of cooling are seen as more efficient. The most common combinations are Liquid-Air Cooling, PCM-Air Cooling, and PCM-Liquid Cooling, and other various possible combinations are shown in Figure 8. PCM is used very commonly as thermal storage come to give with the best thermal uniformity of the battery pack cells. On the other hand, the overall heat capacity of a particular quantity of PCM has its limits. Therefore, PCM alone could not be able to prevent the thermal runaway. PCM must be cooled by other means. Buidin and Mariasiu[45] analyze the investigations and research that have been done so far on the kind, design, and operating principles of Li-ion battery heat management systems. Yaqzan et al. [46] described the Indian battery thermal management scenario. In the condition, unmaintained roads cause traffic congestion and reckless driving and the battery module experiences vibrations, jerks, rapid temperature rises, and excessive discharge rates. The basic classification of BTMS is shown in Figure 8, and in the advancement in this area, many researchers have contributed their work and has been summarized in their following tables (Presently it has been focused on liquid-based cooling and PCM-based cooling only as presented on Table 1: Advanced in liquid cooling system, and Table 2: Advanced in PCM cooling system with various combination of other cooling techniques [47-81].

CONCLUSION AND FUTURE RESEARCH

In addition to EVs, the electrical industry now faces a serious problem with thermal management. Higher heat dissipation rates could necessitate the usage of Lithium-ion batteries with greater capacities. Estimates show that a degree rise in temperature shortens a battery's lifespan by two months [15]. A battery pack's internal temperature differential should also not rise above 5°C [10]. Keeping the battery modules at their ideal operating temperature, which ranges from 25°C to 40°C, results in longer battery life and better thermal performance. Efficient battery module design and thermal management will be a significant step in the global transition to EVs sectors.

The conclusion drawn from the investigations is that the air-cooling method is often lightweight, simple in design, and energy efficient. The liquid cooling approach has higher cooling efficiency and better uniformity of cell temperature than the air-cooling method, but liquid cooling systems require a circulation system, which makes the system complex in structure, weight, and energy consumption. The PCM approach can offer the best cooling performance in terms of the effectiveness of the cell temperature uniformity. However, because the thermal capacity depends on the system's volume, it eventually makes the system heavy or necessitates the use of additional cooling systems to remove heat from the PCM pack. When using the heat pipe notion of cooling techniques, a similar situation might be observed. Additionally, the right heat pipe design and selection are one of the fundamental areas of research that are still undercover. It is understood that the battery thermal management cannot be accomplished with a single cooling strategy. The combination of various cooling techniques which is known as hybrid cooling system is a very significant concept that needs to be adopted for BTMS.

Highlight

- A stand-alone cooling system could not prevent the module temperature in the desired operational temperature at fast charging or discharging.
- Spray or mist air cooling was also found as potential solution for BTMS by maintaining uniform temperature distribution over the cell.
- PCM and Heat-pipe cooling also observed uniformity temperature distribution within the cell. However, longer time is required for cooling in case of stand-alone cooling.
- Hybrid cooling method has a much higher cooling efficiency than stand-alone cooling. PCM based hybrid cooling is much superior to any other combination of cooling.

The elements serve as the driving force behind the effective cooling idea that combines PCM with other cooling systems. Following are the key features of PCM:

- The PCM thermal conductivity can be increased by using a range of high thermal conductivity materials, like copper mesh, graphene nanoparticles, etc.,
- No heat dissipation will occur on the liquid PCM at a certain temperature excess. Therefore, additional mist air needs to be supplied for solidification of PCM. Thus, optimizing the PCM's stacking thickness requires more research with proper mist air cooling.
- The circular structure of layering PCM thickness over the battery cell can promote more heat dissipation in comparison to other PCM structures.

A recent study found that using converging, tapered airflow ducts significantly improve cooling performance and enhances heat transfer in air-cooled lithium-ion battery packs [82]. From the present observation indicates that most current studies use organic PCM, but future studies need inorganic PCM, which has fire-resistant qualities because organic PCM has high flammability. To boost the heat absorption capacity of PCMs over a longer period, more study is also required. The two biggest obstacles facing PCM-based BTMS in conventional settings are lowering the number of additives used and raising PCM quality. Therefore, more effective results may come from an in-depth study of the PCM based hybrid cooling method. The other advantage of using PCM is it can be used easily in all forms of battery types whether it is prismatic, cylindrical, or pouch, also it can be used in the battery module having different stacking styles, with intricate shapes among the cell which is not possible with many other cooling techniques. However, there is lack of information on proper proportion of additives which need to be within PCM, and it is cost effective and unavailability in the markets. Heat pipe (HP) which has the same working principle of PCM, so HP can be the alternate option for the PCM. In heat pipe also the user gets the lots of possibility and freedom of using it because it has a varied range of working fluid, casing material, and casing shape which all can be altered as per the user requirement also it do not require any external power for its working as that of PCM. Thus, combination of heat-pipe and PCM based hybrid BTMS is going to be best solution approach towards future research. Future novel BTMS can be studied using polymer/proton exchange membrane in the battery assembly [83, 84]. On the other hand, as the BTMS gets heavier and more expensive, the cost of the system rises and researchers also need to acknowledge on a battery system's cost analysis.

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AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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