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Advancements in Battery Thermal Management for High-Energy-Density Lithium-Ion Batteries in Electric Vehicles: A Comprehensive Review

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ABSTRACT

Lithium-ion batteries are frequently utilized in electric vehicles because of their high energy density and prolonged cycle life. Maintaining the right temperature range is crucial since lithium-ion batteries' performance and lifespan are highly sensitive to temperature. This study discusses a practical battery heat control system in this setting. The phenomenon of heat generation and significant thermal problems with lithium-ion batteries are reviewed in this work. The studies on various battery thermal management systems (BTMS) are then thoroughly analysed and arranged into groups based on thermal cycle possibilities. Direct refrigerant two-phase cooling, second-loop liquid cooling, and cabin air cooling are all components of the BTMS. Phase change material cooling, heat pipe cooling, and thermoelectric element cooling are all future parts of the BTMS. The maximum temperature and maximum temperature differential of the batteries are examined for each BTMS, and a suitable BTMS that addresses the drawbacks of each system is discussed. Finally, a novel BTMS is suggested as a practical thermal management solution for lithium-ion batteries with high energy density.

Keywords:
Battery Thermal Management System; Electric Vehicle; Lithium-ion

1. Introduction

In the present world due to high environmental pollution and exhaustion of conventional fuel resources, it is essential to focus on areas like increasing the energy conversion efficiency of the system (like IC engines, generators, motors, pumps, etc.) [1]. To meet industrial demand, an in-depth research is being carried out all over the world on thermal management and waste heat recovery; as well as research is also carried out to increase the efficiency of conventional energy systems like IC engines to reduce losses [2]. Though industries are dedicated to the assessment of various options available in this area, technology will be assessed based on three critical criteria: environmental effect, safety, and cost. Among these three criteria, the most important ones are global warming and environmental issues [2]. About 45% of greenhouse gas (GHG) emission in India is due to the road transport sector [3]. Flourishing electric vehicles (EV) and hybrid electric vehicles (HEV) technology

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can considerably decrease GHG emissions due to less consumption of conventional fuel in such vehicles [4]. EVs are a better substitute in the automobile sector to tackle problems like air pollution and weather change while encouraging positive energy development [5].

The development of both EV and HEV battery modules is a principal constituent that will ensure less GHG emission [6]. So the selection of battery is a crucial parameter that needs to be considered in EV and HEV [7]. In 1859, Gaston Planet introduced the first lead-acid battery for commercial use, which leads to the invention of a nickel-based rechargeable battery and then the latest Li-ion battery [8]. Comparing all three industrial batteries based on roundtrip efficiency (%), self-discharge cycles (% energy per day), cycle lifetime (cycles), expected lifetime (years), energy-to-weight density (Wh/kg), power-to-weight density (W/kg), and energy-to-volume density (Wh/L) it is observed that Li-ion battery is superior in all these terms [9]. So the Li-ion battery is dominating the market [10]. Apart from automobiles, the Li-ion battery is also used in energy storage devices, robot systems as well as small unscrewed aerial vehicles.

For high-performance EVs, batteries should support excellent drive performance and should be reliable with high energy density, high power output, high charge efficiency, and low discharge rate with no memory effect [11]. Li-ion batteries have all these above characteristics, so they are suitable for EVs and HEVs [9]. There are different types of Li-ion batteries available in the market; the only difference between them is the cathode material [12]. Classification of Li-ion batteries based on cathode material is as follows $LiFePO_4$, $LiCoO_2$, and $LiMn_2O_4$. $LiMn_2O_4$ has a very high voltage among all three, but its energy density and cycle life are less, so it is not used in EVs [13]. Despite the low cost and high energy density $LiCoO_2$ are not suitable for EVs because of low thermal stability, so they are not safe for EVs [14]. The $LiFePO_4$ battery is an attractive solution for EV applications as it is thermally stable; it has a long cycle life, relatively high energy density, and a low voltage curve [15].

Thermal management of Li-ion batteries is the most challenging aspect that needs to be adequately addressed for its application in EVs [16]. Li-ion batteries used in EVs need to be continuously charged and discharged rapidly, which leads to a large amount of thermal load resulting in relatively large and irregular temperature fluctuations [14]. Li-ion battery works efficiently and safely in a minimum operating range of temperature. The influence of environmental temperature is also high on the operating temperature of the array [17]. The tolerable operating range of Li-ion cells is between -10°C to 50°C [18]. For optimal working of a Li-ion battery, the temperature range is even narrower between 20°C to 40°C [19]. If the battery is operating at a low temperature, it loses its capacity and power. If it is working at a high temperature, then battery performance will degrade rapidly, and battery life will also reduce. It may also lead to thermal runaway. The consequences of a thermal runaway on actual systems can be observed in Figure 1 [20].

Apart from the given temperature range for optimum performance, temperature uniformity throughout the battery pack is also an important parameter [21], to circumvent short circuits or hot spots in a battery pack [22]. As the battery cell voltage is also dependent on temperature, any changes in the temperature of the battery pack will also cause an imbalance in voltage [23]. Consequently, it is desirable to maintain the temperature difference between each cell in a module below 5°C [22].

1.1 Working of Li-ion Battery and Heat Generation in it

For designing the thermal management of a battery, it is important to know how a battery works and how heat evolves in the battery [13]. Li-ion battery is a rechargeable battery. The chemical reaction in a Li-ion battery is a reversible process [24]. This chemical reaction in a battery can take place a hundred times, so it can be used for 2-10 years depending on the application and how it is maintained [25].

All types of Li-ion batteries work similarly. On charging the battery, Li-iron phosphate (LiFePO4) releases positive Li-ion, which passes through the electrolyte and accumulates over the negative graphite electrode [26]. The cell absorbs the energy and stores it during this process. During discharging, the Li-ion moves back to the positive electrode through the electrolyte and releases energy [24]. In the charging and discharging phase, the electrons move in the opposite direction of the Li-ion from the outer circuit [13]. The electrolyte acts as an insulator, so it does not flow through it. The movement of ions and electrons in a cell is interlinked, so if the movement of ions or electrons stops, the other also stops [25].

When the Li-ion batteries are in the charging phase [25], Li-ions move from a positive electrode to a negative electrode, and electrons also move from the outer circuit. The electron and ion combine and Lithium gets deposited on a negative electrode [13]. When the ion flow stops or there is not even a single ion left to flow, it means that the battery is fully charged. During the discharging process of the Li-iron cell, the ions flow from the negative electrode to the positive electrode, and electrons flow from the outer circuit and then supply power to the attached unit (EV, mobile phone, laptop, etc.) [24]. Once all the ions get deposited on the positive electrode, and there are no more ions left to flow, the battery is fully discharged and needs to be charged again. The chemical reactions occurring in LiFePO4 cell are as follows (Figure 1) [27]:

Positive reaction: $Li_{1}\text{- }xFePO_4 + x\ Li+ + x\ e- \rightleftharpoons LiFePO_4$
Negative reaction: $LixC_6 \rightleftharpoons C_6 + x\ Li+ + x\ e\ -$
Total reaction: $Li_1\text{-}xFePO_4 + LixC_6 \rightleftharpoons LiFePO_4 + C_6$

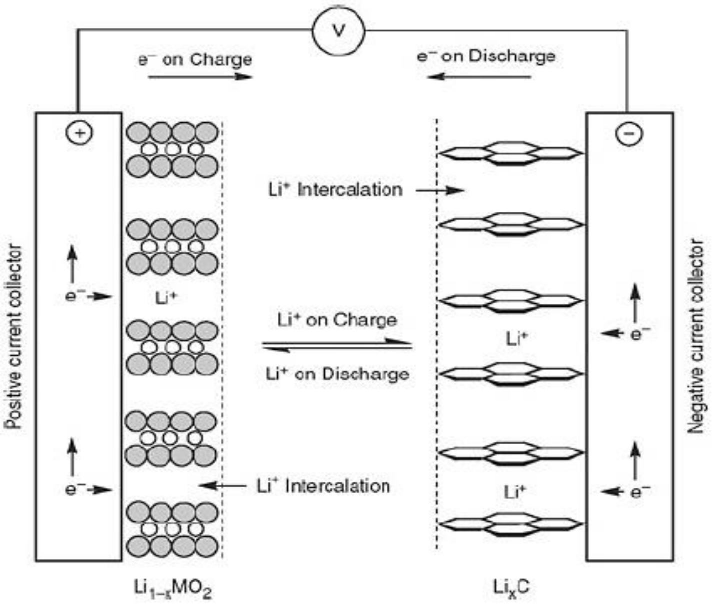
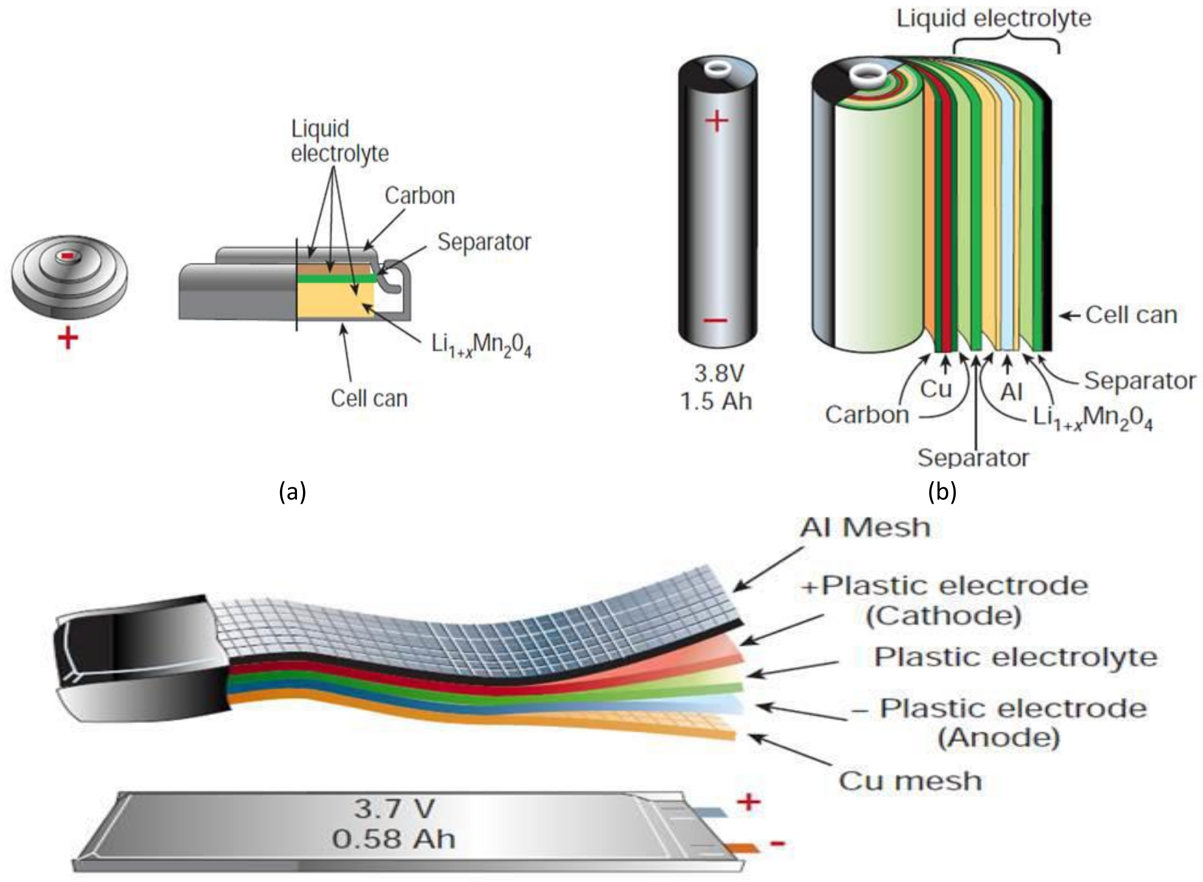


Fig. 1. Chemical reactions in $LiFePO_4$ [27]

Li-ion battery is available in different shapes in the market, as shown in Figure 2 below [28]. The most commonly used Li-ion batteries are cylindrical and coin-type in consumer electronics, e.g., Watches, remote control, etc. The coin type is not used in EVs, whereas cylindrical and prismatic batteries are already being used in EVs [28]. Manufacturers of EVs like BMW and GM are using prismatic cells, and Tesla is using cylindrical cells. The Li-ion cells are arranged in series and parallel arrangements in a battery pack are used in EVs to meet electrical needs as a power source of EVs [29].



(a) (b)

(c)

Fig. 2. Different configurations of the Li-ion battery [27] (a) Coin cell (b) Cylindrical cell (c) Prismatic battery

There are two types of heat sources in the battery. The first one is Joules heat, the one which evolves as the current flow through a circuit and the internal resistance in the channel causes it during the charging and discharging of the battery [27]. The amount of heat generated during the discharging of the battery is limited by the amount of energy stored in the cell but there is no such restriction while charging the cell [30]. If the current is continuously supplied even after the battery is fully charged, heat is generated which is very hazardous [31]. So to control the heat generated due to ohmic losses, it is necessary to keep the internal resistance as low as possible [32]. In the equation given below, the first term indicates Joules heating and the second term means heat generation due to entropy changes. The general equation of heat generated in the battery is used in most of the literature [27].

$$Q = I(u-v) - I\left(T\frac{dU}{dT}\right) \tag{1}$$

The chemical reaction occurring inside the battery during the charging and discharging process may be endothermic or exothermic [33]. Overheating will take place during the exothermic reaction as the chemical reaction will further add heat to the Joules heat, and in the endothermic reaction opposite of it will take place [34]. Anyhow the heat produced during the Joules effect is more as compared to the thermochemical reaction [35]. The heat in the battery is also influenced by the surrounding temperature [23]. If the surrounding temperature is low, the battery pack will give away its heat to the surroundings. If it is high, then the battery temperature will increase, leading to battery overheating or thermal runaway [36]. So to prevent such a situation and keep the battery in its safe operating temperature range, it is necessary to have an efficient thermal management system [37].

For designing and developing an efficient cooling system, in-depth research is going on in the field of BTMS [38]. Different experimental, as well as computational fluid dynamics (CFD) models are studied and compared to identify the optimized system [39] as experimental work involves more time and cost. CFD is widely used to study the effect of different parameters like various configurations of airflow duct, cell arrangement, cell spacing, cooling plate design, etc. on battery performance. CFD is also used to evaluate and validate experimental results [40]. So it is vital to carry out both experimental and CFD studies for BTMS [40].

The BTMS is classified as follows- an air-cooled system, a liquid-cooled system, and others (PCM, heat pipe, and thermoelectric). Air cooling systems are further classified as passive and active air cooling systems [41]. Air-based cooling BTMS has the advantage of a simple design and is easy to handle. But due to the low heat capacity of air, this system fails to maintain the battery in a safe operating range of temperature for EV application [42]. Because of the high heat-carrying capacity, the liquid cooling system can keep the battery in its safe operating range of temperature [43].

Liquid-cooled systems are classified as follows, direct and indirect. In the direct liquid cooling system, the dielectric liquid is in direct contact with the cell, and in the indirect cooling system, a cooling jacket is required to circulate the fluid [44]. The problem with using a liquid cooling system is the intricate design, weight, and leakage [45]. PCM cooling system can maintain cells within a safe operating range of temperature. But due to its low conductivity, it has not been incorporated into EV [46]. Heat pipe needs an additional system to remove heat from the working fluid, and the thermoelectric system has very low efficiency, so it is not famous for EV application [47]. Due to the ineffectiveness of available BTMS for large battery packs used in EVs; it is essential to identify the best possible combination of active and passive cooling systems and address its limitations.

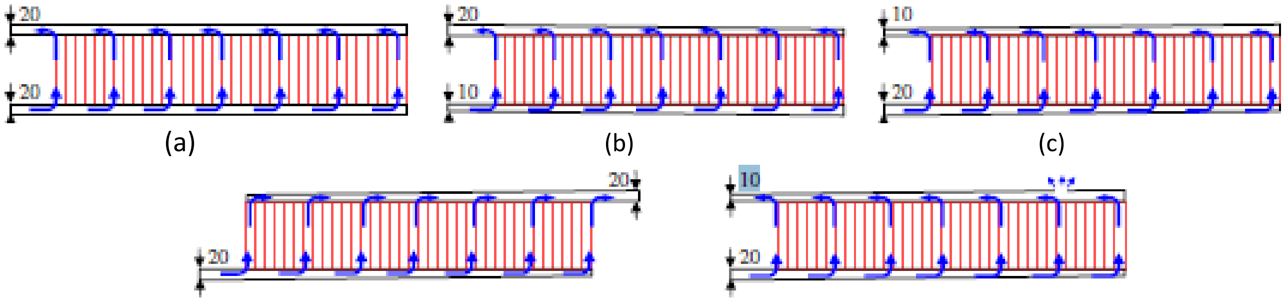
2. Battery Thermal Management Systems

For EVs to work safely and efficiently without any difficulty, it is essential to maintain a battery pack or module in its optimum operating temperature range and uniform cell temperature throughout the pack at a high charge and discharge cycle [39]. To accomplish the above-mentioned work, BTMS is incorporated into EV. Apart from this, BTMS should also take care of extreme weather, which further influences the battery temperature [48]. The main four essential tasks of BTMS are cooling when the cell temperature is too high; heating once the cell temperature is too low, insulation to avoid a sudden change in cell temperature due to external environmental conditions, and ventilation to ensure that hazardous gases are accumulated in battery pack [45].

In addition to above mention function, BTMS should also have the following features; it should occupy less space, it should be light in weight, low maintenance, less number of components, simple design, easy packing, and less use of parasitic power [49]. Air-cooled BTMS is being used in many EVs because of its simple design, which leads to low production and maintenance costs. Different types of air cooling systems available are active and passive air cooling systems [50]. A passive air cooling system is not efficient for BTMS. In an active air cooling system, additional components are required like a fan, blower, and duct to circulate working fluid effectively [51]. Due to low heat capacity and thermal conductivity, the air-based cooling system may not be efficient in maintaining the battery in a safe operating temperature range. This means the amount of air required to cool the system will be more [52]. The parasitic power required to run the fan and blower is also high. For such BTMS, the gap between cells should be broad, so it is difficult to add more cells to a battery pack [53]. Another disadvantage of this system is a large amount of noise is produced due to the fan and blower [51].

2.1 Air-cooled BTMS

To address all the disadvantages of an air cooling system and increase its efficiency, different design has been investigated based on three aspects: geometry of airflow, cell arrangement, and airflow paths. Studies based on these three aspects are summarized in Table 1. Park *et al.,* [54] numerically analyzed the effect of five different configurations of airflow channels on the cooling performance of the battery without modifying the existing battery design. As a result, it is found that type V shown in Figure 3(e) with a ventilation hole tapered from 10 mm to 20 mm in the vertical direction is an optimized configuration. This configuration is capable of dissipating heat efficiently from the battery pack with less consumption of parasitic power as compared to other arrangements.

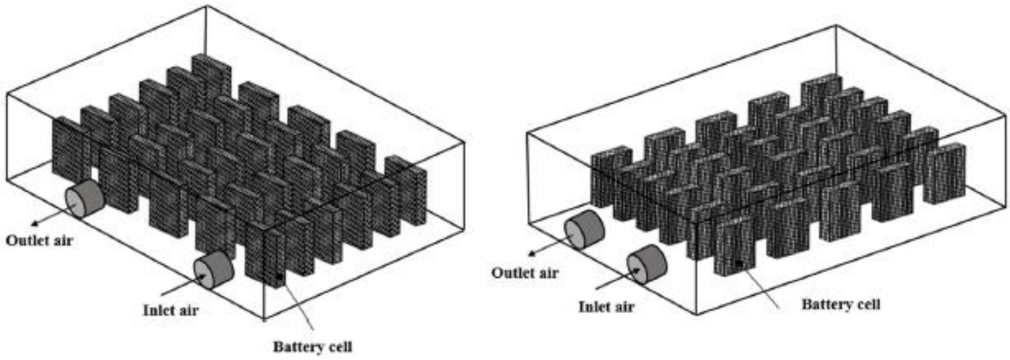


(a) (b) (c)

(d) (e)

Fig. 3. Different configurations of the airflow channel [54]

Xu *et al.,* [55] analyzed the performance of battery cooling for different airflow ducts. The battery pack with a different layout is shown in Figure 4. Research showed that the horizontal battery pack is better as compared to the longitudinal one as the airflow path is shortened in this configuration. The addition of the U-type duct at the bottom increases the thermal contact area for heat conduction.



(a) (b)

Fig. 4. Horizontal and longitudinal layout of battery (a) Horizontal layout battery pack (b) Longitudinal layout battery pack [55]

Dixon *et al.,* [40] investigated the cooling performance of U-type and Z-type ducts (Figure 5). The result shows that the tapered Z-type configuration is efficient in decreasing the airflow rate changes in the cooling duct due to which it can significantly control the changes in cell temperature.

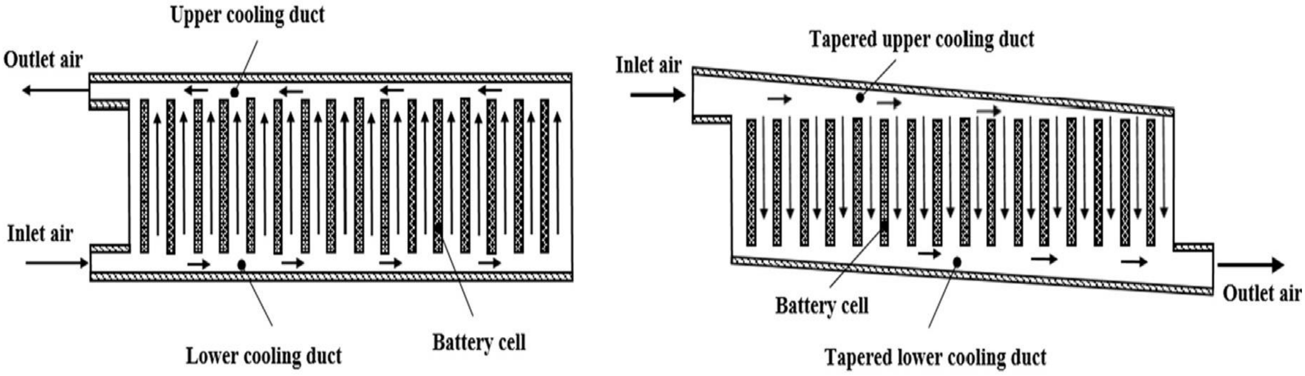


Fig. 5. U-type and tapered Z-type airflow channel [40]

Fan *et al.,* [56] numerically studied the consequence of a change in the cell spacing and airflow velocity on cell temperature. It is observed that decreasing the cell spacing moderately and increasing the air velocity can considerably reduce the cell temperature rise in EV battery packs.

Wang *et al.,* [57] carried out CFD analysis to identify the optimum cell layout and position of a fan for the better thermal cooling performance of a forced air-cooled BTMS system. The different cell layouts studied are as follows (1x24, 3x8, 5x5 rectangle arrays, 19 cells, hexagonal arrays, and 28 cells circular arrays). According to this study, for optimum cooling, the cell should be arranged in a square channel and a fan on top of the module.

Yang *et al.,* [58] developed a thermal model to understand the effect of varying the longitudinal and transverse distance between cells on the heat transfer rate of cylindrical batteries with the aligned and staggered arrangement. For aligned arrangement on increasing the longitudinal length, the individual cell temperature decreases, and on increasing the transverse distance, cell uniformity increases whereas in the case of staggered cell arrangement, increasing the longitudinal distance increases the temperature. Comparing both arrangements, the aligned arrangement has better cooling efficiency and consumes less power. The optimum transverse and longitudinal distances for aligned arrangement are 32 mm and 34 mm.

Mahamud and Park *et al.,* [59] to reduce the problem of temperature non-uniformity in the unidirectional airflow system; a new system with reciprocating airflow was introduced. The numerical result shows that reciprocating air in 120 secs can decrease the non-uniformity in cell temperature by 72% and maximum cell temperature by 1.5°C. These results are achieved because of the disturbances created in the boundary layer of the cell and thermal redistribution.

Yu *et al.,* [60] projected a system with a simple air channel, with airflow in one direction and a vertical turning air channel at the bottom with jet holes for reducing the heat accumulation at specific points in the battery pack. As a result, it is found that this system was able to decrease the heat accumulation at the center of the battery pack and was successful in maintaining the cell temperature difference in the pack below 5°C [60]. The air cooling system may not be an efficient one to be incorporated in a high-performance EV because of the low heat-carrying capacity of air [61]. To overcome the disadvantage of the air cooling system, a liquid-cooled system can be used because the liquid's heat-carrying capacity is high as compared to air [62]. The power consumed by the air cooling system is 40% higher than the liquid cooling system [63]. The air cooling system used in the Li-ion batteries literature is summarized in Table 1.

Table 1
Summary of literature-based air cooling system in Li-ion battery

Author (year)	Major design modification and inferences	Battery load	T_{max} (°C)	ΔT_{max} (°C)
Park *et al.,* [54]	Numerically investigated five different geometric configurations of the airflow channel. Type V configuration with ventilation is better with a taper manifold.	4.18 W	58.2	18.2
Xu and He *et al.,* [55]	Horizontal and longitudinal layout. Horizontal is better (short airflow path).	5.68 W	6.50 (T_{max} rising)	1.96
Sun *et al.,* [40]	Tapered z-type configuration with a greater inlet angle than the outlet is better.	US06 drive cycle	Less than 34	1.1
Fan *et al.,* [56]	Investigated the effect of cell gap spacing and airflow rate on battery cooling. Reducing the cell gap moderately and increasing the air velocity will reduce both maximum temperature rise and ΔT_{max}	6.2 W	33.53 (3 mm gap)	2.81
Wang *et al.,* [57]	Suggested that if a cell is arranged in a square shape and the fan is mounted on top of the battery pack, then it provides better cooling with uniform cell temperature all over the pack.	3C	33.9	2.95
Yang *et al.,* [58]	Studied the effect of different cell layouts on battery pack cooling. From the aligned and staggered arrangement aligned, an arrangement with optimum distances of 32 mm in the transverse direction and 34 mm in the longitudinal was selected.	2C	34.5	0.93
Mahamud *et al.,* [59]	Studied the effect of reciprocating the air system. In which air was circulated every 120 s, this system helps in maintaining uniform cell temperature throughout the pack.	7C	29.6	4
Yu *et al.,* [60]	Introduce a new system with a vertical turning air channel at the bottom with jet holes.	1C	33.1	Less than 5

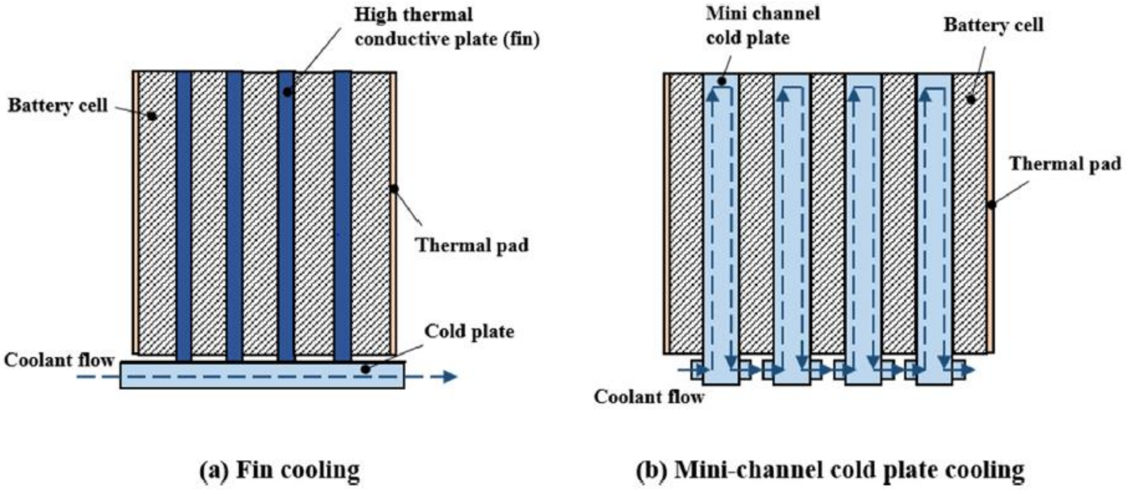
2.2 Liquid-cooled BTMS

The classification of the liquid cooling system is as follows- Direct and indirect liquid-cooled systems.

In the direct liquid cooling system, the coolant is in direct contact with the cell [64]. In an indirect liquid cooling system, the fluid is passed through the cooling channel. The coolant used in direct liquid cooling should be a dielectric fluid, which should not react with cell usually transformer oil [65]. Water and ethylene glycol are used as a coolant for the indirect liquid cooling system [66].

Indirect cooling systems can be further classified as fin cooling systems and mini-channel cold plate cooling systems as shown in Figure 6(a). In the fin cooling system, high thermal conductive fins are attached in between cells which help in spreading the heat equally through the fin. The heat in the fin is further transferred to fluid passing through the single cold plate attached to the fin. The drawback of this system is with time, the reduced temperature difference between fluid and fin, affects the performance of the cooling system [67].

Figure 6 (b) shows how a mini-channel cold plate is attached to the battery cell. The channel is made up of thermally high conductive material. Coolant is continuously flowing through the channel. This system can overcome the problem with the fin cooling system. Each cell is cooled efficiently in this system with uniform temperature distribution. This system usually needs a long and narrow flow passage, which leads to a high-pressure drop. To mitigate this problem, high-pressure and high-power pumps are required [68].



(a) Fin cooling (b) Mini-channel cold plate cooling

Fig. 6. Types of indirect liquid-cooled BTMS [67]

The cooling performance of the mini-channel cold plate and pressure drop depends on the geometry of the channel. So it is important to optimize the geometry of the cooling channel, flow direction, and number of the cooling channel [67]. The study on all these three parameters is summarized in Table 2.

To address the three major issues with cold plate mini-channel that is pressure drop, mean temperature, and temperature uniformity; Kim *et al.,* [69] by changing the width and position of a single serpentine channel as shown in Figure 7 tried to identify the optimized channel. The result shows that keeping the width of the channel maximum, reduces the mean temperature and pressure drop considerably. But for maintaining the uniform temperature distribution along with the cell, the flow channel should be narrow at the inlet and wide at the outlet. Due to this contradiction, it was not possible to find an intermediate geometry. Later they studied the effect of three different boundary conditions (coolant flow rate, the magnitude, and distribution of heat generation) on the performance of a mini-channel cooling plate. As a result of optimization, it was found that input heat flux and coolant flow rate have a greater effect on uniform temperature distribution. Still, these three parameters do not have any effect on pressure drop [70, 71].

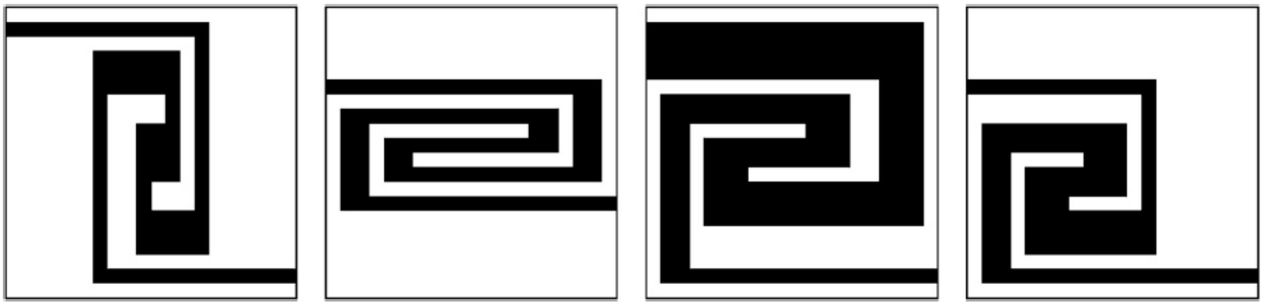


Fig. 7. Optimization of the single serpentine mini-flow channel [70, 71]

Table 2
Summary of studies conducted on the liquid-cooled system in Li-ion battery

Author and year	Major design modification	Cold plate design and liquid used	Tmax (°C)	ΔT_{max} (°C)
Kim *et al.,* [69]	Keeping the width of the channel maximum will reduce pressure drop and mean temperature rise but for uniform temperature narrow channel at the inlet and wide at the outlet is good.	(Single serpentine channel plate)/Water/ ethylene glycol	32.14 (Tavg)	2.53
Jarrett *et al.,* [70]	Observed that input heat flux and the coolant flow rate have a greater effect on uniform temperature distribution but these three parameters do not have any effect on pressure drop.	(Single serpentine channel plate)/Water/ ethylene glycol	37.4	4.95
Jin *et al.,* [71]	Introduced a new design of cold plate with an oblique cut section, which helps in maintaining the rate of convection heat transfer uniform.	Oblique channel plate (water)	<50	-
Huo *et al.,* [72]	Increasing the number of channels and mass flow rate will improve the cooling efficiency and temperature uniformity.	Straight channel plate (water)	58.4 (six channels)	9.02
Zhao *et al.,* [73]	Four or more channels with a mass flow rate of 10-3 kg/s will be optimum to maintain the maximum cell temperature below 40°C	Cylinder (water)	<39 (eight channels)	<12
Qian *et al.,* [74]	Observed that the cold plate cooling system was able to maintain the battery temperature in its safe operating range at a 5C discharge rate.	Straight channel plate (water)	32.5 (five channels with two cold plates)	9
Lan *et al.,* [76]	Introduced a new design instead of plate strips with a cooling channel.	Straight channel plate (water)	28.21	1.21
Wang *et al.,* [75]	Silica liquid cooling plate in which channel was made up of copper. Cooling performance is optimum with two cooling plates with five channels in them.	Silica plate (water)	39.1 2 (five channels)	-

Jin *et al.,* [71] introduced a new type of mini-channel with an oblique cut section to the straight channel. This design helps in avoiding the decreasing trend in convection heat transfer from the inlet to the outlet. Experimental investigation of the same system shows that it is efficient in maintaining the cell temperature below 50°C at a very low flow rate of 0.1 l/min at a heat load of 220 W.

It is also equally important to study the optimization of the number of flow channels and flow direction on the cooling performance of the mini-channel cold plate. Huo *et al.,* [72] examined how a change in the number of flow channels, inlet mass flow rate, and ambient temperature will influence the increase in temperature and temperature distribution for single pouch cells. The outcome of the analysis is that on increasing the number of channels and flow rate, temperature uniformity along with the cell, as well as, cooling efficiency increases.

Zhao *et al.,* [73] numerically studied the influence of changing volume, mass flow rate, flow direction, and inlet size on the cooling performance of cylindrical mini-channel on cylindrical batteries. When the number of channels is four or more than four, and the mass flow rate is 10-3 kg/s, the maximum temperature rise can be maintained below 40°C. Qian *et al.,* [74] numerically investigated the thermal performance of the cold plate and, as a result, found that this system is capable of removing heat from the Li-ion battery pack at a 5C discharge rate.

Wang *et al.,* [75] developed a silica-liquid cooling plate, in this system; the cooling channel is made up of copper. They then studied the cooling performance of this BTMS experimentally and validated it numerically at a different number of plates, cooling channels, and flow directions for different discharge rates. Their research shows that the cooling performance increases as the number of silica plates and cooling channels increases.

Lan *et al.,* [76] proposed a new design with a strip consisting of a mini-channel tube instead of a cooling plate. As a result, found that when all the flow inlets are attached on one side of the battery with more channels at the same flow rate, shows better cooling performance. Table 2 has a summary of the literature part of the liquid-cooled system.

Liquid-cooled systems are capable of removing heat efficiently from battery packs and are incorporated into EVs. The disadvantages of liquid-cooled systems are more number of components, high parasitic power consumption, increased weight, complex design, more maintenance, and a high risk of accidents during leakage [76]. The summary of literature based on the liquid cooling system is summarized in Table 2.

2.3 PCM-cooled BTMS

The other cooling technologies used for BTMS are phase change material (PCM), heat pipes, and thermoelectric. Among these, PCM is a promising technology that can be incorporated into low-capacity EVs [77]. PCM is a material that can absorb and release heat during the phase change process from solid to liquid or from liquid to vapor and vice-versa without any external means of energy. It is used in industries like civil engineering and energy engineering etc. [78–80]. Due to an increase in battery load, a highly efficient liquid-cooled system is used for the same. But as discussed, the liquid cooling system has many disadvantages which can be solved using PCM cooling [80].

The leftmost figure in Figure 8 is a schematic of PCM-based BTMS. It is observed that PCM is a solid block fabricated with a passage in between so that cells can be inserted into it. To release heat absorbed by the PCM, two plates are placed on the top or bottom of the block or either side of the block. During the charging and discharging process of the battery, a large amount of heat is generated as the PCM is in direct contact with the cell, and it starts absorbing this heat. PCM first absorbs sensible heat from the cell due to conduction heat transfer and then absorbs latent heat from the cell till the end of the phase change process. This means that it can handle the sudden change in the thermal load of the battery. It is also capable of maintaining the cell temperature uniform [81].

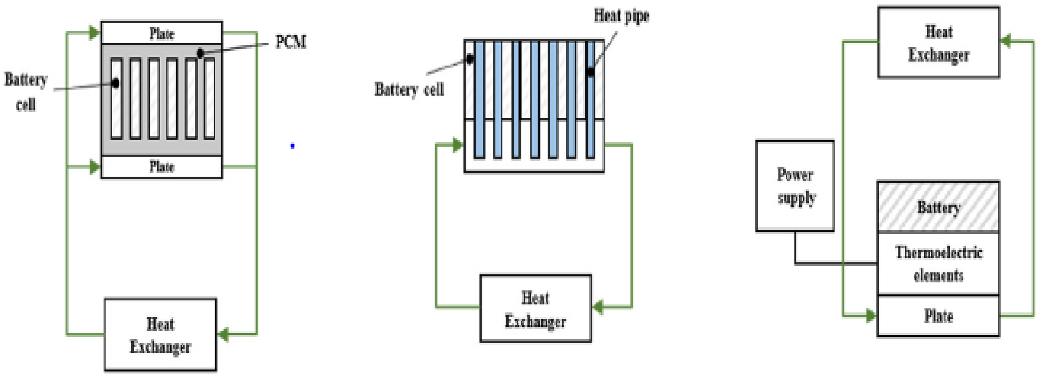


Fig. 8. Schematic diagram of PCM, heat pipe, and thermoelectric cooling respectively [68]

Once the PCM melts completely because of high ambient temperature and constant load on the battery, then it is difficult to continuously operate the battery with only the PCM cooling system [82]. So it is important to remove heat from PCM continuously and to perform this task, some additional system is required. Increasing the mass of PCM can increase the time required for the complete phase change process. As the weight of the system increases, the energy consumption of EVs increases so it is not an appropriate solution [80]. The factors that need to be considered for PCM-based cooling are an optimized mass of PCM and proper selection of PCM. The PCM used for BTMS should have the following properties of high latent heat, high heat capacity, high thermal conductivity, and phase change temperature within the optimum operating range of the battery.

Apart from these, PCM should be chemically stable and should not contain any toxic elements [83]. The most suitable PCM for the BTMS system is paraffin wax. However, the drawback of this PCM is its low thermal conductivity due to which it responds slowly at high thermal load [82]. Thus, a lot of studies are going on to improve the thermal conductivity of this material by adding nanoparticles, metal fins, and porous metal foams [84]. Despite trying many things to improve the thermal conductivity of PCM, it cannot be used for BTMS of EVs because of leakage issues, poor mechanical characteristics, and low rate of heat transfer between the surroundings and PCM [67].

The hybrid PCM suitable for BTMS application can be classified as natural convection cooling, forced convection cooling, and liquid cooling. Ling *et al.,* [61] compared the thermal performance of BTMS with only PCM and composite PCM with a hybrid system. PCM with expanded graphite composite is filled in a battery pack with 20 cylinders arranged in a 5s×4p configuration and forced air is used to remove heat from PCM. As a result, found that for a battery pack with only PCM BTMS, the maximum temperature is more than 60°C and for the hybrid system this temperature is limited to 50°C.

Zhao *et al.,* [85] experimentally investigated PCM/HP BTMS in which heat pipe is used to remove heat from PCM. The condenser part of the heat pipe is further cooled using forced convection air. They also examined the effect of air velocity on the thermal performance of the battery. The result of their research shows that the proposed system is capable of maintaining a maximum battery temperature below 50°C for a long period as compared to forced convection and PCM-based cooling systems.

Hémery *et al.,* [86] designed a new PCM-based active cooling system using liquid. In this system, PCM is filled in an aluminium container on top, and at the bottom of this container, two cooling plates are attached through which water is circulated. The liquid-cooled system was used to increase the rate of the solidification process of PCM. The test result depicts that on keeping the water temperature steady at 22°C if the battery is charged at a 2C rate, the PCM was solidified successfully.

Duan and Naterer, [87] examined the cooling performance of two different types of PCM. In the first case, a heater that replicates the cell is inserted in a container filled with PCM and for the second type; a heater is wrapped with a PCM jacket made up of a flexible PCM sheet. Both PCM designs were immersed in a Nesla bath containing liquid at a constant temperature. Both systems are capable of maintaining the heater within the safe operating range of temperature.

Hallaj and Selman, [88] studied and proposed a PCM-based cooling system for EV applications. Initially, they started with the simulation of an EV battery pack made up of eight cylindrical batteries with 100Ah capacity using finite element software. Results show that the cell integrated with PCM cooling has a more uniform temperature profile as compared to the design which has no PCM. At the end of the C/1 discharge rate, the increase in temperature of the cell with PCM was 53K $h=6.4\ W{\cdot}m^2K$. It was noticed after 24 hrs that the cell temperature increased by 10K.

Kizilel *et al.,* [42] studied the influence of composite PCM on the cooling performance and stability of battery packs at different rates of discharge and cell arrangements. Their research result shows using composite PCM can maintain lower cell temperature and decrease the rate of temperature rise consequently capacity fade is also lowered.

Sabbah *et al.,* [53] compared the effect of forced air cooling and PCM cooling on a low-capacity Li-ion battery for PHEV application. The comparison was studied for different discharge rates, operating temperatures, and ambient temperatures. As a result, it is noticed that without any power consumption, PCM was able to maintain cell temperature below 55°C at a high discharge rate of 6.67 C [53].

To improve the thermal conductivity, to increase the frame strength, and leakage issue of PCM, Wu *et al.,* [89] developed a new PCM structure consisting of copper mesh filled with composite PCM [89].

Rao *et al.,* [90] used paraffin/copper foam composite to remove heat from the battery module of an EV. The experimental set-up consists of 24 LiFePO4 cells surrounded with paraffin and copper foam composite having 37°C melting temperature and 20 PPI porosity with 0.4 g cm-3 density. During constant current discharge at 5 C rate, the maximum battery temperature was below 45°C and the local temperature difference was below 5°C. When the same battery module was installed in an EV, the maximum module temperature was below 40°C and the local temperature difference was below 3°C, so it is an efficient BTMS for an EV.

Liv *et al.,* [91] developed a ternary composite BTMS comprising EG/PCM and LDPE (low-density polyethylene) with fins as shown in Figure 9. PCM having 44°C melting temperature is combined with expanded graphite particle of size (150µm and expansion ratio 220 ml/g) in a ratio of 1:9. LDPE was added in EG/PCM composite in a ratio 7:3. Holes of 18.5 mm were drilled in this composite in which 24, 18650 Li-ion batteries were fixed in 6S×4P configuration. The battery pack consists of four aluminum fins of 110×121 mm^2 and 1.2 mm width and 9 mm height. The experiment was performed and the results were compared with the BTMS without aluminum fins. As a result, it was found that BTMS with aluminum fins has a high discharge rate of 3.5C. The maximum temperature that a cell attained and maximum temperature difference between the cells in a battery pack were less than 50°C and 5°C whereas in BTMS without fins it was 52.9°C and 5.7°C, which shows that fin increases the heat transfer.

Fig. 9. Composite PCM with aluminium fins [93]

Javani *et al.,* [92] studied the effect of PCM on batteries for EVs and also checked the variation in temperature at different PCM thicknesses. By applying PCM on the battery surface, the cell temperature will be uniform and the maximum temperature moves inward as compared to the case without PCM where the maximum temperature was at the bottom of the cell. A 3 mm thick PCM around the cell increases the cell uniformity by 10% and when the thickness is increased from 3 mm to 2 mm, the maximum temperature rise decreases from 2.77 K to 3.04 K. When the PCM was absorbed in a thin foam sheet and applied to the same cell, the T_{max} is 7.3 K less as compared to only PCM around the cell.

Wu *et al.,* [93] optimized the thermal performance of a PCM-based BTMS system and studied the effect of varying PCM thickness, convective heat transfer coefficient, and PCM plate configuration to minimize the size and cost of the system. As the PCM thickness is increased, the cell temperature gradient decreases, however, once the PCM is completely melted then the cell temperature rises continuously due to poor heat dissipation. As a summary of previous literature on PCM-based BTMS, it can be seen that PCM can effectively absorb heat from the battery and maintain the battery at a uniform temperature without any external means of energy. But PCM alone cannot be used as BTMS due to the disadvantages of low thermal conductivity. So PCM composite should be used for large-capacity batteries and it is necessary to build an effective secondary PCM cooling system for batteries used in EVs.

Dibakar *et al.,* [94] compared the cooling performance of two different types of PCM at different thicknesses and ambient conditions on the battery used for EV application. The two different PCMs used in this research are paraffin wax and capric acid. Capric acid reduced the cell temperature to 32°C with 3 mm thickness whereas, in the case of paraffin wax, 9 mm thick material is required to bring down the temperature to 35°C. Therefore, it can be summarized that capric acid is better PCM as compared to paraffin wax, it is cost-effective and easy to handle.

The summary of the previous study can be seen in Table 3. It is observed from the summary that PCM is capable of managing battery heat effectively with minimum power consumption. However, these results were obtained without analyzing PCM cooling effect on the actual battery pack. So it is Wu *et al.,* [67] operating conditions. Heat pipe and thermoelectric cooling are emerging technologies applied to BTMS. The literature based on the phase change material cooling system is summarized in Table 3.

Table 3
Summary of literature on PCM-based cooling

Author (year)	Secondary PCM cooling method	Type of PCM	T_{max} (°C)	ΔT_{max} (°C)
Ling *et al.,* [61]	Forced air convection cooling	RT44HC/EG composite	<46	<3
Wu *et al.,* [67]	Forced air convection cooling	Paraffin/EG/pyrolytic graphite sheets (PGS)	35.65	<2
Zhao *et al.,* [85]	Heat pipe cooling	Paraffin/EG	56	<7
Hemery *et al.,* [86]	Liquid cooling	Paraffin wax (RT28HC)/ aluminium fin	<35	-
Hallaj and Selman., [88]	Free convection cooling	Paraffin wax	-	<2
Kizilel *et al.,* [42]	Free convection cooling	Paraffin wax (RT-42)/ graphite composite	47.5	<0.2
Sabbah *et al.,* [53]	Free convection cooling	PCM/graphite composite	-	-
Rao *et al.,* [90]	Free convection cooling	Paraffin/copper foam	42.33	4.08
Wu *et al.,* [89]	Free convection cooling	Paraffin/EG/copper mesh	61.6	2.7
Liv *et al.,* [91]	Free convection cooling	Paraffin/EG/polyethylene (L-CPCM)	38.5	3.6
Javani *et al.,* [92]	Free convection cooling	n-octadecane	35.28	3.38
Wu *et al.,* [93]	Free convection cooling	PCM/EG composite	53	5
Dibakar *et al.,* [94]	Free convection cooling	Capric acid	32	-

2.4 Heat Pipe and Thermoelectric BTMS

The heat pipe has three parts evaporator, condenser, and isothermal (Figure 10). The evaporator section is attached to the surface from where the heat is to be removed. The liquid coolant inside the heat pipe evaporates and moves to the isothermal part from there it goes to the condenser part. In the condenser, it exchanges heat and converts it into liquid, and flows back to the evaporator. So this system can be used in cooling battery packs [95]. The heat from the evaporator travels to the condenser and from the condenser, some external means need to be available to exchange heat and condense the liquid; this can be anything forced air, liquid, or thermoelectric material [67].

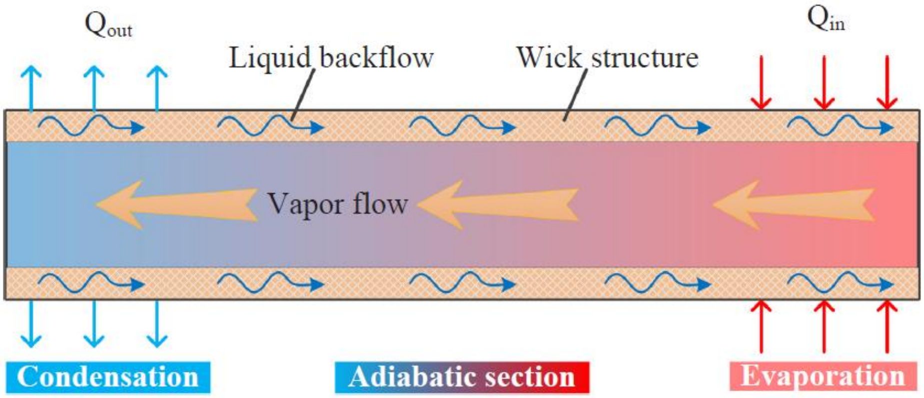


Fig. 10. Construction of heat pipe [97]

Lin *et al.,* [47] *used* heat pipe for thermal management of standard prismatic Li-ion batteries used in EVs. The heat pipe was completely in contact with the cell surface with the help of thermal silica (ZC-801). The heat pipe is manufactured from copper material having a 5 mm outer diameter and 4.4 mm inner diameter. The wick thickness is 0.9 mm with an overall length of 18 mm. Water is used as the working fluid inside the heat pipe. When the heat generation rate of the battery is 50 W then the maximum cell temperature was maintained below 50°C and if the heat generation rate is 30 W, the overall cell temperature difference in a battery pack is below 5°C. As the maximum operating temperature and the temperature difference are within the safe operating range, heat pipes can be used in BTMS for EVs.

Wu *et al.,* [96] developed a transient two-dimensional model to study the effect of different cooling strategies on Li-ion batteries at different states of charge and discharge rates. Comparing the result of three different cooling methods- free convection, force convection, and heat pipe, it is noticed that heat pipe performs better as compared to forced convection. The heat pipe is efficient in reducing the cell temperature at a high discharge rate and is also able to maintain the cell temperature uniform throughout the battery pack.

Tran *et al.,* [97] applied a heat pipe to the HEV battery module; here the heat pipe evaporator section was attached to the copper plate which was further attached to the wall of the battery module (Figure 11). The heat pipe is made of a 7 mm aluminum tube which is enclosed in an aluminum box and the condenser is attached with aluminum fins. Natural convection of condenser is not a reliable solution as some active heat pipe condenser cooling must be employed with minimum power consumption. As this system work effectively in an enclosed chamber, it is a good option for automobile.

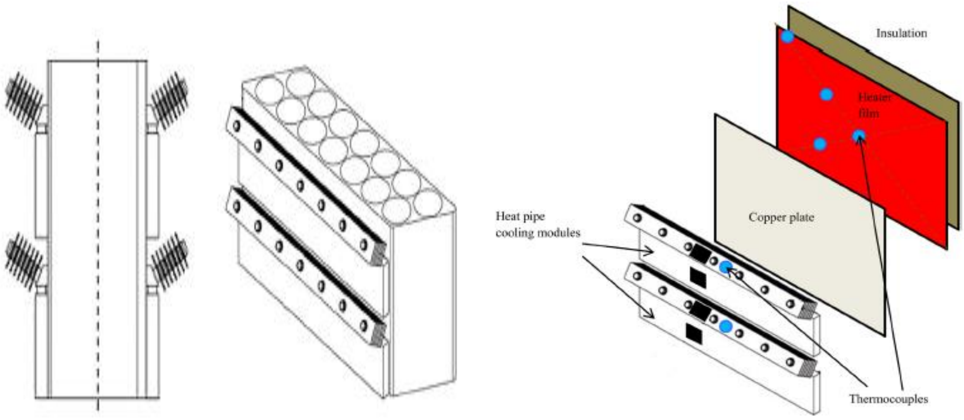


Fig. 11. Heat pipe with aluminum fins [99]

Saw *et al.,* [98] added a copper heat sink to the heat pipe and fins at the condenser side of the heat pipe used to cool the Li-ion battery. Based on numerical analysis, it was found that adding fins to the heat pipe and using forced convection air improved the system cooling performance. This system is very effective in managing heat at the cell level but fails at the pack level. Zhao *et al.,* [99] compared the effect of different methods used to cool the condenser side of the heat pipe. Natural convection, forced air cooling, and wet cooling were used as cooling at the condenser side. The combination of air cooling and wet cooling shows the best result at a high discharge rate keeping the cell temperature distribution at 1.2°C and cell temperature at 21°C.

Liu *et al.,* [100] investigated the performance of an ultra-thin mini-channel heat pipe to cool a prismatic battery used in EV, the battery pack consisting of five prismatic cells was arranged in parallel. Three groups of heat pipes made up of copper material and water as a working fluid were directly pasted between the cells with the help of thermal conductive silicon. They compared UMHP with natural convection-cooled and forced convection-cooled condensers. A result found that a natural convection-cooled condenser is not efficient in battery thermal management and suggested that a forced convection-cooled heat pipe has a better effect on battery thermal management.

In most of the cases, the heat pipe was applied to the prismatic battery. Feng *et al.,* [101] used a heat pipe to remove heat from a cylindrical battery. It is noticed that when the heat pipe is cooled by natural convection, this system fails. But when a fan is used as a forced circulation medium to cool heat pipe, it is capable of maintaining the battery temperature within a safe operating range and the temperature strain is also reduced on the system.

Rao *et al.,* [102] developed a hybrid system consisting of PCM, heat pipe, and natural air cooling. This system was efficient in managing overall battery pack temperature and in this, the PCM solidification was enhanced due to which the battery life cycle increased. Smith *et al.,* [103] used a heat pipe to cool an EV battery having eight prismatic cells and the heat pipe condenser was further cooled by a liquid cooling plate. The heat pipe through an intermediate plate is further connected to a liquid cooling plate. The liquid coolant enters the cold plate at 25°C and is pumped at a speed of 1l/min. This hybrid system works better as compared to only a liquid cooling system, as the leakage problem in the liquid cooling system is reduced in this system and the system design is also simple. The heat pipe cooling system is efficient in removing heat from the battery; it is more suitable for the prismatic battery. In the case of a cylindrical battery, the heat transfer contact area is less so some extra heat sink needs to be attached to the system, and apart from that the condenser needs to be attached to any of the active cooling systems or forced cooling systems to maintain the battery operating temperature within safe range [67].

Thermoelectric substances can be used in two different ways as thermoelectric generators or thermoelectric coolers. The first one is based on see back effect in this system; the waste heat energy is converted into electricity and the second one is based on the Peltier effect in which electricity is converted into thermal energy which can be used for cooling or heating an element [67]. TEC is already used in luxury cars. It is made using P and N-type semiconductors sandwiched between thin ceramic plates. On passing current through them heat flux is generated between them [63]. The cold side of the TEC is attached to the battery and the hot side is attached to the cooling plate through which a coolant flow either air or liquid. When the current is passed through a thermoelectric circuit, the heat is transferred through it from the battery to the cold plate side. When current is transferred in the opposite direction, it can also be used to heat the battery [104].

The advantages of using thermoelectric cooling are low maintenance, less space consumption, moderate weight, additional mechanical components not required so no moving parts and no noise, wide operating range of temperature, and long life. Though there is a lot of advantage to using this system, due to low efficiency, it is not used in BTMS. Few researchers tried using thermoelectric cooling for BTMS which is classified as air-cooled thermoelectric BTMS and water-cooled thermoelectric BTMS [67]. Alaoui *et al.,* [104] applied TEC to Li-ion pouch cells having 60 Ah capacity. Here the battery was attached to an aluminum plate on one side and extruded heat sink on the other side where four blowers were placed near the heat sink to efficiently remove heat from the battery to the surrounding. This system consumed more energy with 0.9 COP during the constant current test and 1.2 during the normal driving cycle.

Liu *et al.,* [105] developed a new system using liquid as a coolant in TEC-based BTMS. They tested on a battery pack with eight cells having 100 Ah capacity. Numerical analysis of this system shows that at a 1C discharge rate, this system is efficient in maintaining the cell temperature below 40°C and temperature difference below 1°C. The only problem with this system; the contact area between the cell and TEC is less so there is uneven temperature distribution along with the cell which may deteriorate its performance. This problem can be addressed by inserting metal having high thermal conductivity in between it.

The merits and demerits of different types of cooling systems for BTMS are discussed elaborately in this chapter for EV application.

3. Discussion

Throughout the review, it was found that a quantitative comparison of each thermal management system was a little difficult because of the difference in battery type, charge capacity, discharge rate, and other external conditions. Thus, it is important and helpful to assess different types of BTMS operating in the same conditions to carefully understand the thermal characteristics of each system. Among the BTMS, the air-based BTMS system has a simple structure, due to which it has a low operating cost and requires low maintenance. The disadvantage of an air cooling system is its relatively low heat-carrying capacity, so this system can be employed for short-distance EVs which have low-capacity batteries and therefore less thermal load. An air-cooled system is not suitable for high-performance EVs because in such EVs the heat load will be large, so more amount of air is needed, subsequently, more power and space consumption which is a serious drawback of the system. Recently, the indirect liquid-cooled system was widely employed in EVs because it has better cooling efficiency as compared to air cooled system. The disadvantages of a liquid-cooled system are it has high manufacturing and operating cost, it needs more components, and it requires more maintenance as well as leakage. The heat transfer in liquid cooling can also be enhanced using Nano fluids [106].

The PCM-based cooling system is used to overcome the disadvantages of the previous two types of BTMS. This type of BTMS can offer larger heat transfer performance by using phase change heat transfer. In addition to this, since PCM material is applied on the surface of the cell, the latent heat transfer is exchanged at a uniform temperature. This helps in maintaining the uniform battery temperature. PCM-based BTMS needs a very less number of components compared to air-cooled and liquid-cooled systems, which makes it more reliable. The major drawback of PCM-cooled BTMS is it needs more time to re-solidify, and it is unable to respond continuously to the thermal load of the battery. The thermal conductivity of PCM is very low with a problem of volume change. The thermal conductivity of PCM can be enhanced using nanoparticles [107]. The heat pipe BTMS is also a passive cooling system, due to which it is a little difficult for this system to actively control the temperature. The only advantage of heat pipe systems is they consume very low parasitic power as compared to other BTMS. Thermoelectric systems are capable of controlling the temperature precisely, but this system consumes more power because of its low efficiency.

The batteries used for EV applications may have different requirements based on the types of vehicles. Batteries are the powerhouse of EVs so they must be capable of storing a large amount of energy with minimum weight for better mileage. The weight of the battery casing can be reduced by using composite materials [108]. Exclusive research is going on in the same field, so it is expected that in the future Li-ion batteries will have improved energy and power density. The development in the energy density in Li-ion batteries is shown in the Figure 2. This development indicates that in the future, the EVs mileage increases, due to which thermal challenges will also escalate as a result of abnormal heat emissions and heat accumulation. Each BTMS discussed has its own merits and demerits and so it has limited application for high energy density batteries. Therefore, more attention is paid to combining BTMS, which can magnify the advantages and disadvantages of each type of BTMS system. But the studies on hybrid BTMS system do not have any practical application and was studied for some specific cell application. Therefore, in the future, it is important to study the thermal performance of hybrid BTMS in the battery module and pack integrated into real EVs experimentally [109, 110]. Besides this, the cost, weight, and size of the hybrid BTMS must be considered for EV application.

4. Conclusion

To improve the performance and safety of EVs, it is important to integrate BTMS into them. This paper broadly reviews and categorizes the existing BTMS studies based on different types of cooling mediums used. BTMS is classified as air-cooled, liquid-cooled, PCM-cooled system, and heat pipe as well as thermoelectric cooling. BTMS using air has been applied to many EVs because it is readily available in the atmosphere. But, it consumes more parasitic power to run units like fans and blowers as the heat-carrying capacity of air is very low. The air cooling system has the advantages of simplicity, low weight, cost, and low maintenance. However, it has drawbacks such as poor cooling performance due to the air's low heat capacity, fan noise issues, and limited space utilization. To boost cooling in this system, many studies have focused on optimizing its geometry, such as air channels, cell layout, and airflow routes. Liquid cooling systems can be more efficient but come with the drawbacks of increased complexity, cost, and weight due to added heat exchangers and circuits. The two-phase cooling system uses a two-phase heat exchange of materials, resulting in better cooling performance at low mass flow rates compared to liquid cooling systems that perform single-phase heat exchange. Additionally, the system reduces complexity and weight by eliminating liquid circuits and extra heat exchangers.

BTMS two-phase cooling system is not commonly used in EVs, but it has great potential for energy efficiency and thermal performance. The PCM cooling systems can absorb a lot of battery heat at the same temperature through a phase change process with minimal energy consumption. However, this system struggles with the low thermal conductivity of PCM, continuous battery heat load post-PCM phase change, PCM leakage, volume changes, and inhomogeneity during repeated melting/solidifying processes. The heat pipe cooling system can transfer heat more efficiently because of its higher thermal conductivity compared to general PCM. However, it needs to be combined with a cooling plate due to the limited contact area with the battery. The thermoelectric element cooling system can precisely control the battery temperature by adjusting the current in the TEC. However, its low efficiency signifies that in-depth studies are not being conducted yet.

As a result of the review, it was observed that the direct comparison of each type of BTMS was not possible due to differences in battery type, capacity, and operating conditions, the batteries were tested. However, the merits and demerits of each type of BTMS were identified. Therefore, to develop a more effective BTMS, it is critical to select an appropriate BTMS based on the requirement of EV and to use a hybrid BTMS system to compensate for the disadvantages.

In the future, the thermal load on EV batteries will likely increase because of their higher energy density. To address this issue, it is important to develop a BTMS that integrates various options, including PCM as well as hybrid.

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