Chapter 10
Battery Thermal Management System for EVs: A Review

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10.1 Introduction

With the rapid reduction in fossil fuels, increasing crude oil prices, and environmental pollution, the demand for electric vehicles (EVs) and hybrid electric vehicles (HEVs), has been increasing significantly. Nowadays many countries are setting up policies and assist financially to support the development of EVs to overcome the demand and environmental pollution regulations on greenhouse gas (GHG) emissions [1–6] Keiner et al. (2019); Nazari et al. (2019); Chen et al. (2019a); Sun et al. (2020); Kim et al. (2019a). These policies show strong support for the healthy growth of EVs over this decade. According to Global EV Outlook 2021, with Sustainable Development Scenario, predicts that, the global EVs can reache up to 230 million vehicles excluding two and three wheelers by the end of this decade with a stock share of 12%. However, one of the critical challenges in developing EVs is a high-density energy storage system that could support fast charging, high mileage, and high-performance driving with lighter weight. Compared among all energy storage currently used, lithium-ion batteries are being widely used owing to their high energy density, high power capacity, low self-discharge rate, and long service life Smas et al. (2015); Lowe et al. (2010). The Li-ion batteries include Li-Co, Li-Fe, Li-Mn, and Li-NiCoMn batteries Vazquez-Arenas et al. (2014). These Li-ion batteries also do not have the memory effect. The memory effects are commonly found in nickel–metal hydride and nickel–cadmium batteries. The memory effect in the batteries occurs if the batteries are recharged continuously if it gets discharged partially which slowly

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decreases the usable capacity of battery leading to reduced working voltage. These batteries suppressed the energy density of all earlier competing batteries, due to which these batteries are extensively used for automobiles.

However, thermal management and safety are still significant challenges in the development of lithium-ion batteries. The thermal management of the battery is more challenging with fast charging and high-performance driving as there is rapid heat generation. These Li-ion batteries' capacity, service life, performance, and safety are susceptible to temperature Bandhauer et al. (2011). The temperature change in any battery is inevitable as heat is released during charging and discharging due to chemical reactions, which highly depend on the rate of these processes Smith and Wang (2006). In addition to this, resistive heating also affects the thermal behavior of the batteries. The operating and even storage temperature can harm the performance and lifespan of batteries. The lower temperature will significantly reduce the battery capacity; however, the high temperature negatively impacts battery life and capacity. It is essential to study the characteristics of the specific battery to optimize its performance.

Generally, the operational temperature for EV batteries ranges from − 40 to 60 °C Ma et al. (2018). However, to obtain the EV's optimal performance and prolonged lifespan, the battery is to be operated in the range of 15 to 35 °C, and the temperature gradient within the battery pack needs to be maintained below 5 °C Kitoh and Nemoto (1999); Ramadass et al. (2002); Rugh et al. (2011). The operating temperature outside this range harms the performance of the battery. The lifespan of Li-ion batteries drops by two months for each temperature degree rise Zhao et al. (2015). In a hot climate without battery cooling, aggressive driving may decrease battery life by 2/3 Yuksel et al. (2017).

If a Li-ion battery is operated at a lower ambient temperature for a long term may also result in a considerable decrease in battery life due to dendrites formed on the battery's anode Friesen et al. (2016). Safety is the main concern in the large-scale Li-ion batteries, but the formation of lithium dendrites hampers the safe working of Li-ion batteries with graphite anodes Wang et al. (2017). The electrolytes react with lithium dendrites violently at higher temperature to generate gases which increase the internal pressure of the battery continuously leading to problems like electrolyte leakage and battery explosion. The growth of lithium dendrites destroys the thermal stability of solid electrolyte interphase (SEI) film. In addition, the reaction between electrolytes and lithium dendrites increases the decomposition of SEI films, reducing the thermal run away temperature of the battery Yamaki et al. (1998). The performance of Li-ion batteries is seriously affected if operated below subzero temperatures as their internal resistance increases drastically below − 20 °C, which ultimately leads to a reduction in their lifespan and performance Hu et al. (2020).

Another significant aspect of the battery safety is a thermal runaway, caused mainly by local overheating. Thermal runaway is a severe safety issue, which refers to an uncontrolled chain reaction in the battery that is very difficult to stop once started and may result in smoke, fire, and even explosion. The total heat released from the batteries of about 12% is sufficient to trigger thermal runaway in adjacent batteries Feng et al. (2015). The local overheating due to mechanical, electrical, or thermal abuse can trigger the thermal runaway Feng et al. (2018).

Therefore, the battery thermal management system (BTMS) is essential for maintaining the appropriate temperature range, reducing the temperature gradient within the battery pack, and preventing thermal runaway. There are two main parameters to be considered to evaluate the performance of BTMS: the maximum temperature rise and temperature gradient within the battery pack. Numerous methods for BTMS have been proposed by researchers, which can be classified as shown in Fig. 10.1.

The pre-heating BTMSs are used to pre-heat the battery pack, which is used in cold operating conditions. In cold climates the performance of Li-ion batteries decreases leading to decrease in battery capacity, sudden increase in battery resistance, difficulty in charging and discharging and severe degradation leading to decrease in life cycle. Thus there is need of battery heating equipments to keep Li-ion batteries working satisfactorily under low temperature environment. There are three ways of battery heating: self-internal heating, convective heating, and mutual phase heating Khan et al. (2017). Self-internal heating is most simple and efficient and it gains the heat during battery charging and discharging. In convective heating method, the battery can be heated both internally and externally. In this methodology, the fan and resist heaters are used and heat generated by resist heaters is passed convectively using fan. The mutual phase heating method is rarely used and in this methodology the battery output power is used for heating itself Ji et al. (2013). Cooling BTMSs

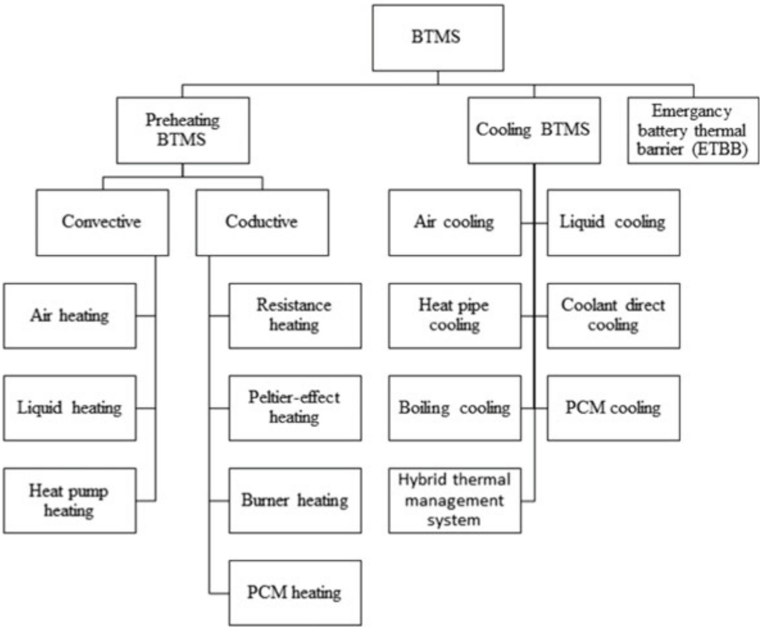


Fig. 10.1 Classification of BTMS

are used for effective cooling of the battery, operating at higher ambient temperature, whereas the ETBT are designed to suppress the potential hazard of the thermal runaway. This chapter presents the heat generation phenomenon, different and significant BTM systems available with pros and cons. In this chapter, the approach is to have qualitative analysis only; and the quantitative analysis can be a future scope.

10.2 Heat Generation in Batteries

Heat generation in batteries is a significant con of battery systems. Two types of heat generation occur in batteries: 1. Irreversible Q_{irr} (through resistance offered to flow of electrons], 2. Reversible Q_{rev} [through chemical reactions while charging/discharging) Arora et al. (2017). This phenomenon can be presented in equation format as

$$Q = Q_{\mathrm{irr}} + Q_{\mathrm{rev}}$$

where,

$$Q_{\mathrm{irr}} = I^2 R_{\mathrm{int}};\ Q_{\mathrm{rev}} = -\mathrm{IT} * \frac{\mathrm{d}E_{\mathrm{ov}}}{\mathrm{d}T}$$

In these equations, I is current, R_{int} is internal resistance, T is temperature. The R_{int} is a function of SoC (state of charge) and temperature. Through many numerical and experimental analyses, it has been found that the heat generation in the batteries depends on multiple factors, out of which the significant factors are Current, Temperature, SoC, SoH (state of health), and Electrochemistry. One can find an ample amount of literature discussing the methods to reduce heat generation and strategies to increase the dissipation of heat generated from the batteries. While designing lithium-ion batteries, two significant parameters need to be considered, i.e., heat capacity and thermal conductivity Buidin and Mariasiu (2021); Kim et al. (2019b). The coming sections will discuss the methods to increase the dissipation of heat generated from batteries.

10.3 Air Cooling

Air-cooled BTM systems use air as a working fluid to cool the batteries. Many configurations of air-cooled BTMS are proposed till date depending upon the criteria mentioned in Table 10.1. Each configuration has its pros and cons, so one must select the best suitable configuration for a defined application. Battery conditioning, i.e., maintaining battery temperature, can be done by cooling or heating the battery and

Table 10.1 Classification of the air-cooling system

SN.	Criteria for classification		Classification	
1	Air driving mechanism	Natural cooling	Forced cooling	
2	Source of air supplied	Active cooling	Passive cooling	
3	Cooling structure	Parallel cooling	Serial cooling	Mixed cooling
4	Contact type	Direct cooling	Indirect cooling	
5	Thermal cycle	BTMS with VCC	BTMS without VCC	

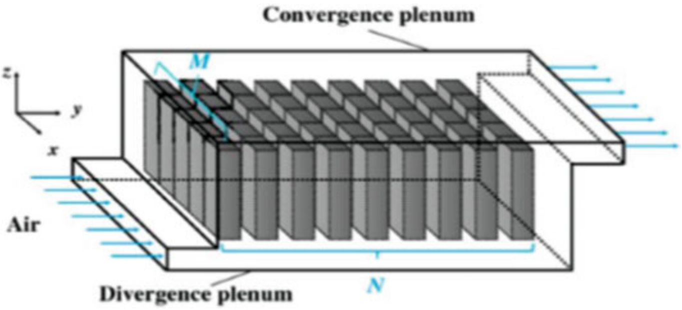


Fig. 10.2 Typical air-cooled BTM system.

providing ventilation through the system Kim et al. (2019b); Lin et al. (2021a). The BTM systems using air as working fluid have the advantage that the same air maintains the ventilation. The typical air-cooled BTM system is shown in Fig. 10.2.

Various researchers presented many other air-cooled BTM systems [refer to Fig. 10.1] along with this typical system. The air-cooled BTM systems are simple in construction and are low-cost systems. Air's heat carrying capacity is much less than most conventional liquids used for liquid-cooled BTM systems; hence liquid-cooled BTM systems have higher efficiency Lin et al. (2021a). The liquid BTM systems are discussed in the next section in detail (Fig. 10.3).

10.4 Liquid Cooling

As discussed in the previous section, liquids have higher heat carrying capacity, and hence liquid-cooled systems perform better than air-cooled systems. These systems compact, achieve, maintain a low temperature, and are uniformly distributed. Because of all these advantageous characteristics, it has been accepted widely in electrical vehicle EV applications. With these pros, the liquid-cooled systems also have cons like; more weight, complex structure, leakage, and additional power for liquid circulation. Prismatic battery systems adopted liquid-cooled systems due to their simple construction compared to cylindrical battery systems. The most commonly used

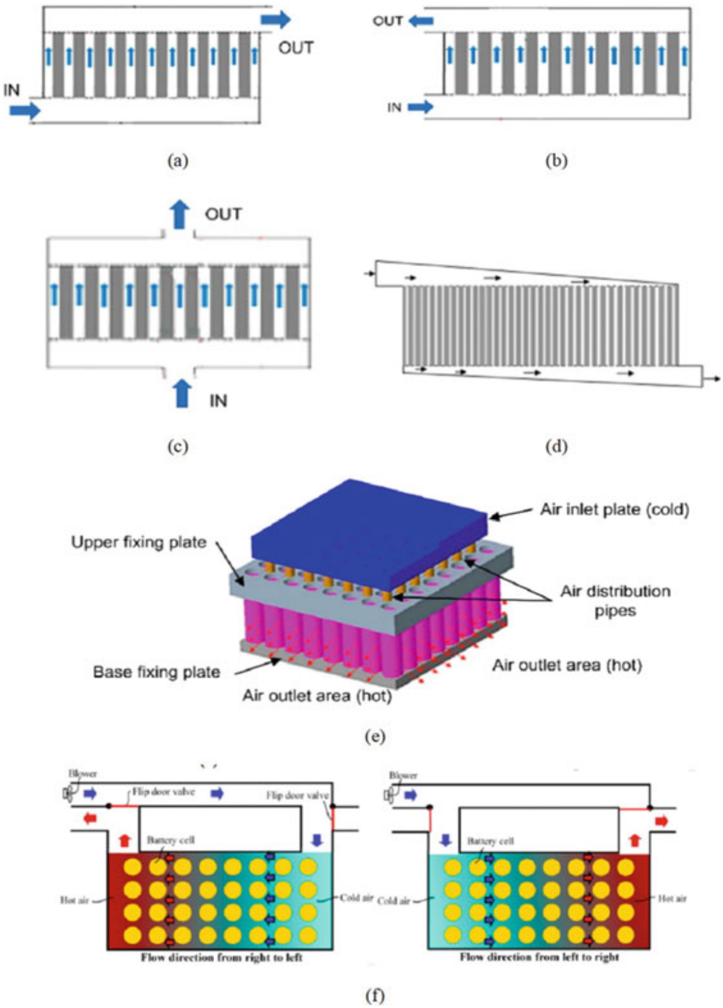
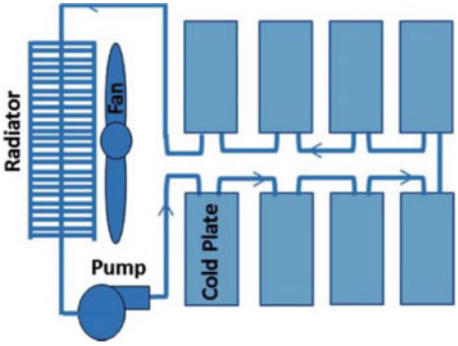


Fig. 10.3 Different air-cooled BTM systems; **a** Z type, **b** U type, **c** symmetrically modified type, **e** distribution pipe type, **f** reciprocating airflow type

working fluids are water and ethylene glycol. The indirect contact type liquid-cooled systems are preferred over direct contact type systems due to their more practical approach Lin et al. (2021a). The typical liquid-cooled BTM system is shown in Fig. 10.4.

Fig. 10.4 Typical liquid-cooled BTM system Lin et al. (2021a)



10.5 Phase Change Material Cooling

The load on batteries goes on increasing day by day; thus, the BTMS is using multi-channel liquid cooling loops as a powerful cooling technique. However, this technique is complex and consumes more power. So to overcome these difficulties, cooling using phase change material (PCM) is one of the good options Sharma et al. (2009). The PCM is a promising alternative to conventional air and liquid cooling due to its easy coupling with passive cooling Buidin and Mariasiu (2021). The phase change material (PCM) technique is used in many industries to absorb or dissipate the heat through the phase change technique without energy consumption Elefsiniotis et al. (2014), Kuznik et al. (2011), Jaguemont et al. (2018). Sharma et al. (2015) have extensively investigated and classified phase change materials. There is a lot of different material available which can be used as PCM for the BTMS application. It includes organic materials such as organic acid, paraffin wax, and alkane, and some inorganic materials such as salt hydrate, aqueous solution, and eutectic Chen et al. (2019b). The different PCM materials with the properties required for thermal management system are given in Table 10.2. The critical parameter that needs to be considered for PCM application to BTMS is selecting appropriate phase change material. The PCM chosen should have large heat carrying capacity, latent heat, thermal conductivity, and temperature range during phase change within the battery's operating temperature range. Also, the PCM must be non-toxic, stable chemically, and has a shallow sub-cooling effect during the process of freezing Jaguemont et al. (2018).

PCM stores or releases heat as its phase changes from one state to another at a particular temperature. The PCM schematic is used for battery cooling, as shown in Fig. 10.5 by Kim et al. (2019b). As shown in Fig. 10.1, the cells are in direct contact with the phase change material (PCM), and these are solid material blocks either modeled or machined such that the cells can be inserted easily. Four plates surround the PCM, one on the top and bottom side each and one on the right and left side each, which is used to release the heat gained by the PCM. A tremendous amount of heat generation occurs during the battery charging or discharging process. The heat generated is passed to phase change material, as they are in direct contact

Table 10.2 Different PCM materials with its characteristics

Property or characteristics	Paraffin wax	Non-paraffin organics	Metallics	Hydrated salts	Sugar alcohol	Polyethylene glycol
Heat of fusion	High	High	Medium	High	High	High
Thermal conductivity	Very Low	Low	Very high	High	High	High
Melt temperature (°C)	−20 to 100+	5 to 100+	150 to 800 +	0 to 100+	70 to 180	−50 to 62.5
Latent heat (kJ/kg)	200–280	90–250	25–100	60–300	290–350	105–183
Corrosive	Non corrosive	Mildly corrosive	Varies	Corrosive	Non-corrosive	Corrosive
Cost	Moderate cost	High cost	Costly	Low cost	Low cost	Low
Thermal cycling	Stable	At higher temperature, decomposition can take place	Stable	Unstable over repeated cycles	Stable	Stable
Weight	Medium	Medium	Heavy	Light	Medium	Medium

with the battery cells via conduction mode of heat transfer depending upon the temperature difference. The phase change material initially absorbs the heat as latent heat. As the phase change process starts, it absorbs a considerable amount of latent heat at a constant temperature and will absorb the heat until it reaches the melting point temperature. Thus, PCM can work under sudden battery temperature variation without sudden temperature rising and temperature unevenness Wilke et al. (2017).

Numerous research works have been carried out to enhance the low thermal conductivity of PCM Azizi et al. Azizi and Sadrameli (2016) developed a BTMS using wire mesh plates of aluminium and PCM to increase thermal efficiency conductivity. The wire mesh plates with higher voltage values are considered over the

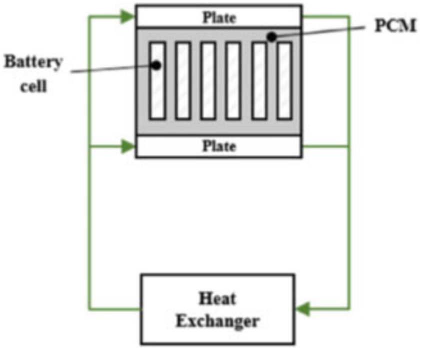


Fig. 10.5 Phase change material (PCM) cooling technique Kim et al. (2019b)

aluminium foams to quickly fill pores during PCM phase change. Yan et al. Yan et al. (2016) have designed and developed a sandwich model of PCM for the battery pack cooling. The PCM board has an excellent ability during normal and abusing conditions over normal air or cooling board. Yan et al. have also summarized that as the heat capacity of PCM increases, it also increases the rate of heat dissipation of the battery pack. Zhao et al. (2017b, 2018) used a compact structure of PCM cores into the cylindrical batteries, resulting in high heat transfer efficiency. It has been observed from the experimental result that such construction consumes less PCM and achieves a smaller rise in the temperature of the battery and higher temperature uniformity compared to external BTMS. A research carried out by Al-Hallaj et al. Kizilel et al. (2008) summarized that if a battery pack is working at 45 °C atmospheric temperature and 2C discharge rate, 90% PCM pack capacity can be utilized; however, 50% utilization can take place without PCM before the temperature of battery increased above safety limits. Paraffin wax as PCM is the most appropriate material. Still, it has the limitation of lower thermal conductivity as other phase change material Wang et al. (2015), i.e., it responds slowly during high-demand applications. Several studies are going on to enhance the thermal conductivity of PCM without disturbing their good properties. There are three ways to enhance PCM's thermal conductivity: first by using metal fins, second by using thermally conductive materials such as nano-powdered carbon, and third by using porous materials such as an expanded graphite matrix (EGM) Kim et al. (2019b). Though many efforts are taken to improve PCM's thermal conductivity, it is still challenging to use for automobile BTMS due to a few limitations like poor mechanical properties, leakage, and a very low heat transfer rate between PCM and the surroundings.

The use of BTMS shows a significant enhancement in the overall performance of BTMS. Due to its fluidity, the PCM technique improves thermal uniformity, like observed in the direct liquid cooling technique. In addition, the unique benefit of the PCM technique is that the energy utilization efficiency is higher due to the latent heat of PCM. The PCM is extensively used to pre-heat EVs for energy-saving Zhao et al. (2020). PCM technique is more flexible as the melting point of PCMs can be varied with various components. Thus, the BTMS can work well in different conditions by varying its melting point. The latent of PCM will help BTMS work in extreme cases for a more extended period. Thus, PCM is a practical approach over forced air cooling, and it simplifies the BTMS structure Kizilel et al. (2009). However, one of the difficulties of using only PCM for BTMS is that the PCM cannot be operated continuously because it may melt entirely due to hot environmental conditions or continuous charging and discharging of batteries Ling et al. (2015). Hence, an extra cooling system that can transfer the PCM heat to the surrounding is essential. Also, adding PCM mass increases the phase change completion time, improving the overall weight, and hampers EV performance. Therefore, the mass of PCM should be determined appropriately. Thus, the PCM technique is generally combined with active cooling methods to overcome these difficulties, gaining PCM's thermal energy storage capacity.

The conventional cooling systems like air-cooling BTMS require extra power and liquid-cooling BTMS requires complicated equipments to assure the effect. Therefore, PCM-based BTMS is nowadays becoming more popular. PCM-based cooling can absorb the heat and the battery pack temperature can be kept under normal working temperature range for longer duration without any external power supply. The PCM-based cooling system has simple structure and operation, no need of additional equipment, excellent temperature control performance without any energy consumption and low cost. PCM-based cooling can enhance the heat dissipation efficiency by using in combination with fillers like expanded graphite (EG) and metal foams for their higher thermal conductivity. In last few years, the trend on new energy development and environment protection has rapidly developed PCMs. The unique feature of PCM of keeping temperature constant during the phase change process, allows it be used for building and solar energy storage, thermal equipment management Alimohammadi et al. (2017), Dyer et al. (2002), Krishna et al. (2017), Alshaer et al. (2015), Salimpour et al. (2016) and other related fields. The large amount of phase change latent heat allows PCM to absorb and loose heat to work within the normal working temperature for longer duration. The use of PCM also reduces the temperature difference between each battery more efficiently. The rapid development in PCM since last few years the different composite PCMs has application in power battery packs and showed an effective solution to overheating of batteries and can maintain the temperature within 45° during discharging of battery.

In addition, the PCM shows very good performance of providing quick response to temperature and efficient control of temperature but still there are few difficulties that cannot be neglected such as low thermal conductivity, leaking problem, and lower strength. Many researchers used various techniques such as addition of fillers of higher thermal conductivity into the PCM or using PCM matrix impregnated with EG Mills and Al-Hallaj (2005) to overcome these difficulties. But still there are few difficulties to be overcome in the future like super cooling and is the major difficulty which will affect the thermal performance and PCMs stability and it is important to be improved and investigated further. Further the unbalanced requirement and availability of PCM, higher average cost of PCM and therefore how to manufacture PCM at lower cost is the major problem that needs to be addressed.

10.6 Hybrid Thermal Management System

The combined use of two or more basic BTMSs is considered a hybrid BTMS technique. The various basic BTMS has their benefits and limitations, respectively. The hybrid BTMS can use the help of basic BTMS and improve thermal performance Zhao et al. (2020). However, the hybrid BTMS has a few drawbacks with its energy consumption, volume, and weight Zhao et al. (2020). The hybrid BTMS is classified into different types and is listed in Table 10.3 and is discussed.

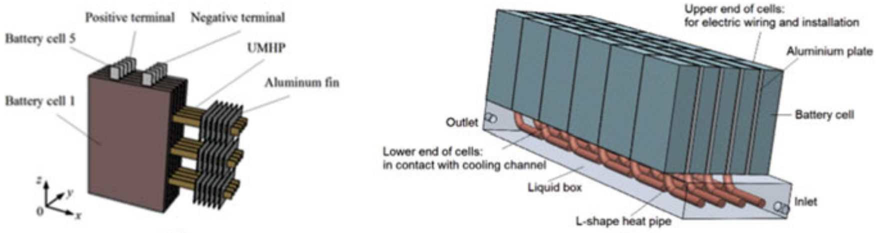
A hybrid BTMS is always shown higher thermal performance using higher power consumption but possesses a complex structure. In such systems, HP is always

Table 10.3 The primary classification of hybrid BTMS

Sr. No.	Type	Hybrid BTMS
1	HP combined with either liquid or air cooling	HP + liquid
		HP + air PCM + HP
2	PCM combined with HP	CM + HP + Air PCM + HP + liquid
3	PCM combined with Liquid or air active cooling	PCM + liquid
		PCM + air
4	TEC combined with other BTMS	TEC + liquid + Air
		PCM + TEC
5	Liquid combined with air	Liquid + air

provided with forced-air cooling as shown in Fig. 10.6a and liquid cooling as shown in Fig. 10.6b. The HP coupled with forced-air cooling BTMS uses an ultra-thin micro heat pipe (UMHP) connected to a fan. In this the individual cell of the pack is numbered from cell 1 to 5 in y-direction. All the UMPH of sintered copper–water is fixed between the cell cavity and it forms a sandwiched like structure. There are total 3 groups of pipes with spacing in between in z-direction and all the groups have 4 pipes arranged parallel with spacing in y-direction. The heat generated by cells is conducted more efficiently; the evaporator of all the pipes is attached to the cell surface by using silicone. The cooling system is provided with air convection on each side of condenser pipe and aluminium fins with spacing in-between in x-direction and are attached to condenser pipe with silicone. It has been observed that the use of UMHP decreases the maximum temperature by 7.10 C from the starting of discharging at a 2C rate over without HP system. Also, the maximum temperature can be maintained below 400 C with 4 m/s speed Liu et al. (2016). As observed in Fig. 10.2b, the heat pipes are inserted into the cavity of each battery cell and condenser and evaporator of it is attached to aluminium plate for temperature flattening. Below the battery pack the liquid channel acts as a heat exchanger to supply and remove the heat from battery as per requirement. This will result in bi-directional advantage by the heat pipe so that system will provide either heating or cooling without moving parts.

The BTMS using only PCM or composite PCM (CPCM) cannot maintain the battery pack temperature in a required range due to accumulation of heat caused due to poor natural air-cooling technique. Thus, active cooling methods are required to recover the thermal energy storage capacity of PCMs. Figure 10.7a shows a BTMS system that uses CPCM (expanded graphite/enhanced paraffin and copper mesh) and copper fins exposed from the CPCM to improve heat transfer rate Wu et al. (2016). The battery pack composed of 5 batteries and 6 CM-PCMP is arranged in a compact sandwich structure. All the batteries were arranged in series connection and a fan was used to such that the air flows into the channel from one side of pack. The two battery packs of same configurations with and without PCMP were assembled for comparison purpose. The experimental result shows that the CP-PCMP shows improved

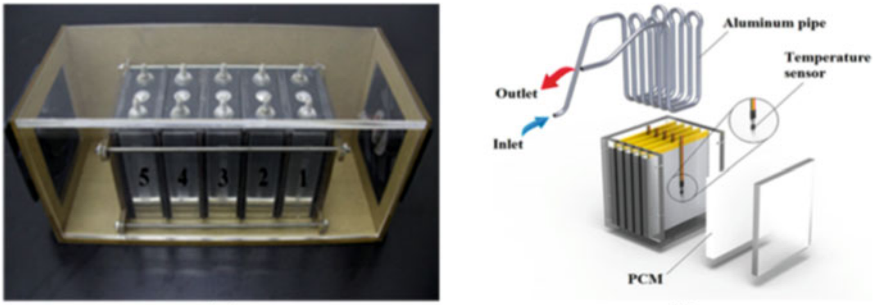


(a) (b)

Fig. 10.6 Hybrid BTMS combined with **a** ultra-thin micro heat pipe and **b** liquid cooling Liu et al. (2016)

performance for dissipation of heat and temperature uniformity over PCMP and traditional ANC technology under harsh working environment. However, the BTMS shown in Fig. 10.3b uses PCM and cooling water pipes Hekmat and Molaeimanesh (2020). The experimental setup operates in three modes of active, passive, and hybrid with small modifications. The battery module consists of 5 prismatic Li-ion cells of 148 × 129 × 4 mm3 and 3.8 V normal voltage and of 5000 mA h nominal capacity. All the cells are held vertically in a glass box with 14 mm distance in-between them. Each cell surface is provided with sensor for temperature measurement. The cells are fixed in the module and are sealed and separate six zones are created for employing aluminium cooling pipes. Meanwhile, the zones can be filled with silicone oil or PCM or can be left with free air. It has been observed that, the use of silicone oil or PCM in-between cells decreases the maximum temperature to 450 C and 320 C respectively; however maximum temperature difference decreases to 5.10 C and 1.20 C respectively compared to atmospheric air. However, the BTMS shown in Fig. 10.7b uses PCM and cooling water pipes Hekmat and Molaeimanesh (2020).

Ling et al. have compared the battery's performance with the PCM technique and PCM combined with forced air convection cooling Ling et al. (2015). The experimental setup has 20 Li-ion cells of cylindrical geometry with five and four cells in



(a) (b)

Fig. 10.7 Hybrid BTMS using PCM with **a** air Wu et al. (2016) **b** liquid Hekmat and Molaeimanesh (2020) series and parallels, respectively. They used RT44HC/expanded graphite (EG) with appropriate melting point temperature and high specific phase change enthalpy. It has been observed that the maximum temperature of the battery pack using PCM only increases above 60 °C in two cycles. However, PCM coupled with forced air convection cooling controlled the maximum temperature below 50 °C in all processes. Further, Wu et al. have studied the cooling performance of battery modules using para- fin/E.G. composites with pyrolytic graphite sheet (PGS) and without PGS by varying the convective heat transfer coefficient Wu et al. (2017). It has been observed that PCM with PGS module shows better temperature uniformity and heat dissipation performance for last charge/discharge cycles.

The PCM is easy to combine with hybrid BTMS, and PCM can enhance thermal uniformity Zhao et al. (2020). In a similar way of coupling the PCM with active cooling like air and liquid, HP can also be associated with the PCM because of its quick response and improved efficiency. The PCM can be filled between HP and HTF or battery cells, as shown in Fig. 10.8a Zhang et al. (2020). In this experimentation prismatic LiFePO4 batteries having capacity of 2.7 Ah are used. The battery pack has total 18 cells, 3 cells are arranged in parallel and 6 cells in series. The system is provided with a protection board to avoid overcharge or over discharge. Total 10 heat pipes are used in the system. The evaporation sections of heat pipes are placed in between every two batteries however the condenser is extended outside the battery pack and compactly placed with metal foams. In order to reduce the thermal contact resistance, the contact surface is coated with the layer of thermally conductive adhesives. It has been observed that, the maximum temperature of battery pack without auxiliary fan with 1C, 3C, and 4C discharge rates are under 45 °C. Also at higher discharge rate of 5 °C, the maximum temperature difference can be controlled within 5 °C.

Lei et al. (2020) coupled PCM, spray cooling, and HP to control the battery pack's temperature, as shown in Fig. 10.8b. In this hydrated salt is for battery thermal management and is filled in and around the batteries. The hydrated salt is used due to its high specific latent heat, appropriate melting point, and large density. It has been

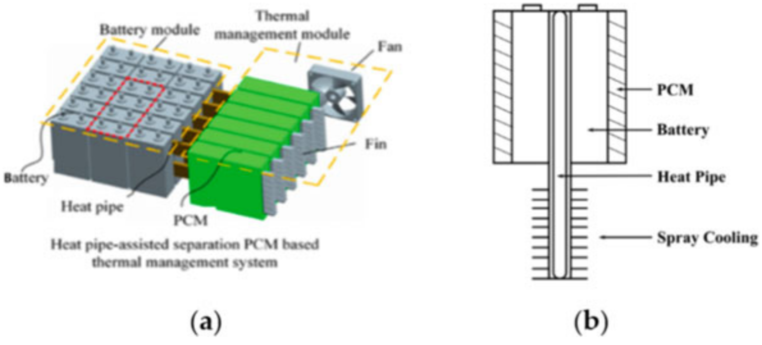


Fig. 10.8 Hybrid BTMS **a** HP provided with PCM as BTMS. Zhang et al. (2020), **b** HP provided with PCM associated with spray cooling Lei et al. (2020)

observed that, this technique holds the battery surface temperature rise below 8 °C, at a discharge current of 24 A and a high atmospheric temperature (40 °C).

Zhao et al. (2017a) tested the PCM and heat pipe (HP) coupled BTM module experimentally. It has been observed that PCM and HP as a BTMS can maintain the maximum temperature below 50 °C for a more extended period compared to air and PCM-based BTMS techniques. Hemery et al. Hémery et al. (2014) designed and developed a PCM and active liquid coupled hybrid BTMS to cool the melted PCM. They used the two water-cooled plates above and below the PCM in the experimentation's aluminum cans. The electric heaters are used instead of cells. It has been observed that PCM was completely solidified when the battery charging was done at a 2C rate after discharge three driving cycles where the temperature of the water was maintained constant at 22 °C.

Thermoelectric cooling (TEC) is not generally considered for BTM of EV because of its poor efficiency. But it is mainly used in electronics cooling applications due to its compact construction Zhao et al. (2020). Few of the researchers have coupled TEC with hybrid BTMS for improving the rate of heat transfer. Figure 10.9 shows the typical layout of TEC coupled with hybrid BTMS Li et al. (2019). Lyu et al. Lyu et al. (2019) have coupled the TEC with active cooling techniques. The condenser side heat is transferred using TEC, and the forced air helps the TEC pass the heat to the outer side. It has been observed that the battery surface temperature reduces by 12 °C from 55 °C. Song et al. Song et al. (2018) designed and developed a BTMS for standby batteries with thermoelectric semiconductor device coupled with PCM, as shown in Fig. 10.10. The experimental setup was tested to study the heat preservation time (4.15 days), cooling time (14 h) circularly under atmospheric temperature (323 K).

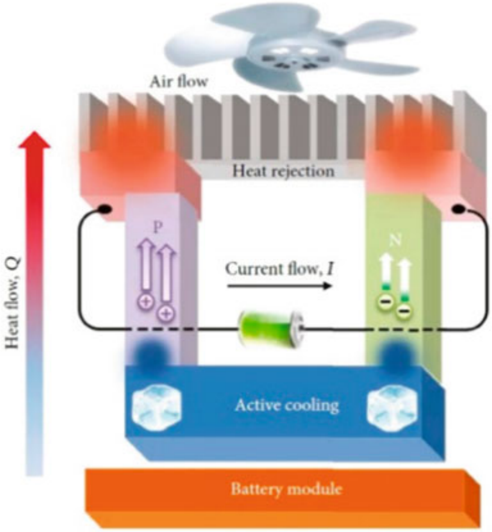


Fig. 10.9 The schematic layout of TEC in hybrid BTMS Li et al. (2019)

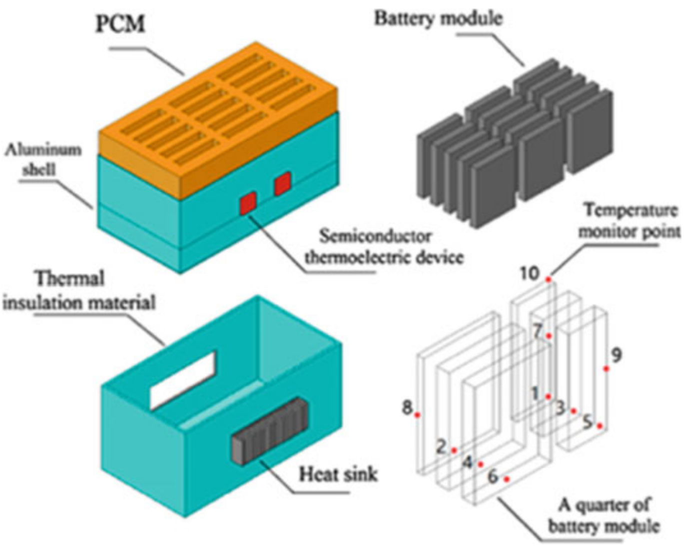
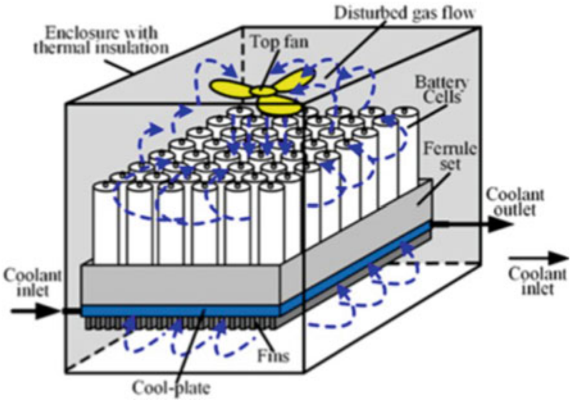


Fig. 10.10 The hybrid BTMS of PCM coupled with TEC Lyu et al. (2019)

Some of the researchers used forced-air and liquid cooling technique simultaneously. Wang et al. designed a BTMS, as shown in Fig. 10.11, by combining an LCP and the gas circle Wang et al. (2017). They studied the effect of various structures, the intensity of the liquid and gas cycles on the thermal performance of BTMS. It has been observed that the system with a fan under LCP could make a fully developed flow field. Compared to cooling with LCP only in the vacuum-packed battery, the maximum temperature and temperature difference are lowered by 3.88 and 3.45 K under the condition of total heat generation of 576 W.

Fig. 10.11 The schematic of liquid coupled with air BTMS Wang et al. (2017)



10.7 Heat Pipe Cooling

Temperature is the most critical parameter which directly affects battery efficiency. The BTM system is a system which ensures the overall performance of the battery along with its life, reliability and prevents economic loss. This is the best system to control the temperature of battery thermal management systems and has lightweight, portable size, flexible geometry, and low cost. This is a passive system because it does not consume power. The heat pipe is a heat conduction device that usually works by keeping the partial vacuum in the casing and transporting the maximum heat even at minimal temperature differences. An aluminum fin to the heat pipe section efficiently enhanced the heat dissipation rate. The utilization of heat pipe has migrated into various applications because of its wide range of working temperature. It is expanded in various sectors to invent a more structured system that improves thermal efficiency. The enhancement in the efficiency of heat pipes containing the Nanofluids can be increased because of having a high heat transfer rate compared to conventional fluids. In this case, efficiency is depending on the type of nanoparticles and their concentrations. But for a certain application, it may create complexities for high-temperature applications. Thermal conductivity is the most important parameter to enhance the heat transfer performance of a fluid. The flat, micro heat pipe reduces weight, high heat flow density, space and improves the heat transfer rate when subjected to forced convection and better temperature uniformity. Figure 10.12 shows the working of a heat pipe.

The different phase change materials are used in lithium-ion battery along with a heat pipe such as paraffin copper foam, paraffin, EG composite, meliorate paraffin with composite paraffin with nanoparticles, carbon fiber, Cu mesh, refrigerant R404a, paraffin expanded graphite, and hydrated salt is the coupled cooling methods, i.e., heat pipe cooling method Lin et al. (2021a). Because of the higher thermal conductivity, the heat transfer rate of the heat pipes is more efficient than the phase change material. It works on the pooled effect of phase change and thermal conductivity. They generate heat transferred to the heat pipe through the battery's modules and then absorbed by the phase change material. In the system, the heat source is coupled to the evaporator section. The operating fluid moved to the condenser by absorbing heat from the heating side. The working fluid condenses in the condenser with the help of an external heat exchanger, i.e., it can be air or liquid and finally comes to the evaporator section. This system doesn't require an external power source as it's an utterly natural

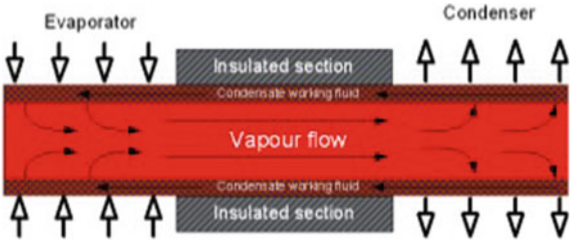


Fig. 10.12 Heat pipe working cycle Jouhara et al. (2017)

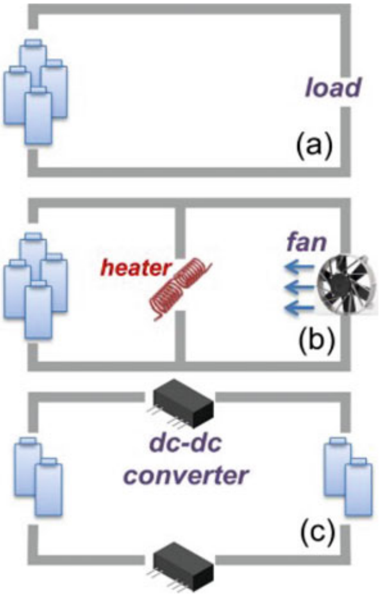


Fig. 10.13 Heating strategies using battery power **a** self-internal heating, **b** convective heating, and **c** mutual pulse heating Ji and Wang (2013)

circulation method. Still, this method's disadvantage is that it cannot be adequately cooled during the discharge of the cycle.

In some cases, forced convection cooling should be applied to have better cooling performance. Heat pipe cooling methods have excellent heat transfer efficiency work on the principle of evaporation. For better thermal performance, the BTM module uses air to control the temperature by changing air velocity. The coolant flow rate also enhances the performance of the heat pipe. In recent years pulsating pipe or oscillating heat pipe gives the high thermal performance. It is combined with a multi-physical system to control the temperature and its optimum range, i.e., from 20 to 45 °C, ensuring low battery temperature for long-time cycling Zhao et al. (2020).

The comparison between the basic and hybrid battery thermal management techniques is given in Tables 10.4 and 10.5 respectively.

10.8 Battery Heating Strategies

The temperature variation inside the battery is the critical parameter in the battery's overall performance, life, and reliability. Lithium ion batteries play a crucial role as a power source in the electric vehicle field due to their high-power density. At low temperatures, its performance is drastically degraded because of low diffusivity and poor conductivity, and finally, it tends to damage the battery life. There are various strategies of battery heating methods shown in Fig. 10.1. These strategies are essential for the functioning of an effective battery management system. In the

Table 10.4 Comparison between basic BTMSs

System characteristics		Air	Liquid (direct)	Liquid (indirect)	PCM	CPCM	Heat pipe
Cooling capacity		Very small	High	Medium	Very small	Small	Medium
Energy consumption		Low	High	Medium	None	None	None
Temperature distribution		Uneven	Uneven	Uneven	Even	Even	Uneven
Size		Large	Medium	Compact	Large	Large	Compact
Weight		Light	Heavy	Medium	Heavy	Heavy	Light
Complexity		Simple	Medium	Complex	Medium	Medium	Simple
Cost		Low	Medium	Medium	Low	Medium	High
Reliability		High	Medium	Medium	Very low	Low	High
Adaptability	Cylindrical	Easy	Moderate	Difficult	Easy	Easy	Difficult
	Prismatic	Moderate	Difficult	Easy	Easy	Easy	Easy
	Pouch	Moderate	Difficult	Easy	Moderate	Moderate	Easy

Table 10.5 Comparison between hybrid BTMSs

System characteristics		PCM + Air	PCM + Liquid	HP + air	HP + liquid	PCM + HP + air
Cooling capacity		Medium	High	High	Very high	High
Energy consumption		Low	Medium	Low	Medium	Low
Temperature distribution		Even	Even	Uneven	Uneven	Even
Size		Large	Very large	Large	Medium	Very large
Weight		Heavy	Very heavy	Light	Medium	Heavy
Complexity		Medium	Complex	Medium	Complex	Very complex
Cost		Medium	High	High	Very high	High
Reliability		Low	Very low	High	Medium	Low
Adaptability	Cylindrical	Easy	Easy	Difficult	Difficult	Easy
	Prismatic	Easy	Easy	Easy	Moderate	Easy
	Pouch	Moderate	Moderate	Easy	Moderate	Moderate

convective heating strategy method, battery heat both internally and externally. The power source, i.e., fan, produces a convective flow, and this heating process occurs. It requires the battery, cell, fan, and other components in a closed-loop system Ji et al. (2013). The air or liquid can be used for convective heat transfer. Heat creation occurs in the self-internal heating process while the charging and discharging process heats the cell through internal resistance. Heating performance can be improved by adjusting the frequency and amplitude through pulse charging and discharging.

In some cases, heat generation devices are used in batteries such as nickel foil for heating purposes. The heating performance can be increased from − 20 to 0 °C in 12.5 s without consuming more battery energy. These can be achieved by using suitable electrolytes and modified anode material to restore the thermal performance of the battery. There are four criteria for heating strategy evaluations: electric energy consumption or driving range, heating time, the durability of the battery, and overall system cost. So different heating strategies can be compared with the above four criteria. The convective heating process takes minimum time for heating, and mutual pulse heating requires the least battery capacity.

Battery degradation, cost, enhancement of thermal performance, and durability are the most critical factors in the electric battery. The main objective of the battery is to work efficiently for the stated period for different operating ambient temperatures. The experimental implementation and verification of all strategies will be a challenging task in the future.

10.9 Conclusions

The objective of the chapter is to discuss different BTM systems and their pros and cons; the following qualitative conclusions can be drawn based on the literature available.

1. Air-cooled BTM systems are simple in construction and cheap too, but those are low efficient.
2. The liquid-cooled BTM systems are also more efficient and compact, but these are heavy and have leakage issues.
3. The PCM cooling technique is a good choice for BTMS as it can absorb battery heat at a constant temperature with a minimal amount of energy consumption. However, the significant hurdles of PCM are its low thermal conductivity, leakage, and battery heat load management after complete phase change of PCM. The composite PCM can overcome these hurdles and requires further investigations.
4. Hybrid BTMS is an emerging trend in developing BTM systems, and it has shown great potential and feasibility, specifically for extreme working environments. Hybrid BTMS are more flexible and efficient and can overcome the hurdles of basic BTMS.

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