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Review article

Review of battery thermal management systems in electric vehicles

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ABSTRACT

Lithium-ion batteries are the most commonly used battery type in commercial electric vehicles due to their high energy densities and ability to be repeatedly charged and discharged over many cycles. In order to maximize the efficiency of a li-ion battery pack, a stable temperature range between 15 °C to 35 °C must be maintained. As such, a reliable and robust battery thermal management system is needed to dissipate heat and regulate the li-ion battery pack's temperature. This paper reviews how heat is generated across a li-ion cell as well as the current research work being done on the four main battery thermal management types which include air-cooled, liquid-cooled, phase change material based and thermo-electric based systems. Additionally, the strengths and weaknesses of each battery thermal management type is reviewed in this study. It was determined that air cooled systems are suited for short-distance travel electric vehicles, liquid cooled are for electric vehicles that require long-distance travel, larger battery packs and for high thermal loads, phase change material based are for electric vehicles with constant thermal loads and stable ambient temperatures and thermo-electric battery thermal management systems are best best suited in conjunction with the other types for better control.

1. Introduction

With the increasing demand to lower the carbon footprint of the transport sector, automobile manufacturers are rapidly developing electric vehicle (EV) technologies and increasing EV production. In 2021 alone, the global sales of EVs reached 6.6 million which tripled the 2019 sales figures [1]. Despite the growth in demand, there are still several factors that hinder the widespread adoption of EVs in the general automotive market. Among the issues faced by consumers are the EV's lack of reliability for long-distance travel and the EV's short vehicular lifespan, particularly with regard to the longevity of the EV's battery pack [2].

There are several factors that affect the performance of an EV battery pack but the main factor is its susceptibility to thermal effects. A conventional EV li-ion battery pack operates optimally between 15 °C to 35 °C. If the li-ion battery pack operates below 15 °C, the overall capacity drops and the battery's internal resistance increases [3]. Conversely, temperatures above 35 °C could potentially lead to an irreversible reaction occurring across the li-ion battery pack and an increased risk of thermal runaway [4]. Additionally, it can also accelerate the capacity drop of the li-ion battery [5]. Given the critical impact of thermal effects on an EV battery pack's performance, continuous advancements in efficient cooling systems will benefit the overall longevity and safety of the pack.

Various thermal management strategies are employed in EVs which include air cooling, liquid cooling, solid–liquid phase change material (PCM) based cooling and thermo-electric element based thermal management [6]. Each battery thermal management system (BTMS) type has its own advantages and disadvantages in terms of both performance and cost. For instance, air cooling systems have good economic feasibility but may encounter challenges in efficiently dissipating heat during periods of elevated thermal stress. In contrast, liquid cooling, whether implemented through direct or indirect methodologies, exhibits notable effectiveness in heat dissipation, albeit potentially incurring greater implementation costs. PCM based cooling mechanisms utilize the large latent heat capacities of materials undergoing phase transitions between solid and liquid states to conduct heat away from the battery packs which demonstrates potential in enhancing thermal regulation. However PCMs have low thermal conductivity which will have to be enhanced through the integration of thermally conductive materials [7]. Thermo-electric element-based systems, leveraging the Peltier effect for heat transfer, afford meticulous temperature control, though frequently associated with higher implementation costs.

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Nomenclature

Abbreviations

BTMS	Battery Thermal Management System
CFD	Computational Fluid Dynamics
CPCM	Combined PCM with EG
EV	Electric Vehicle
EG	Expanded Graphite
HP	Heat Pipe
li-ion	Lithium-Ion
PCM	Phase Change Material
TEC	Thermo-Electric Cooler
TEG	Thermo-Electric Generator

Notations

bat	Battery
CaO_3	Calcium carbonate
CO_2	Carbon dioxide
H_2O	Dihydrogen oxide
$MgCl_2$	Magnesium dichloride
$Mg(NO_3)_2$	Magnesium nitrate
max	Maximum
SiO_2	Silica
TiO_2	Titanium dioxide
T_{max}	Maximum battery temperature (°C)
T_{bat}	Battery operating temperature
ZnO	Zinc oxide

Units

A	Amperes
Ah	Ampere hour
C	Discharging rate
°C	Celcius
I	Nominal current (A)
K	Kelvin
Pa	Pascal
m	meter
m^3/s	Cubic meter per second
m/s	Meter per second
mm	Millimeter
mAh	Milli ampere hour
OCV	Open circuit voltage (V)
Q	Heat generation rate (W)
s	Seconds
V	Nominal voltage
W	Watts
wt%	Weight percentage

Currently, the EV industry predominantly relies on air and liquid BTMS, as their cooling capacity is adjustable based on the EV's load demand [8]. While these methods are effective, there are various under explored BTMS alternatives with significant potential such as with thermoelectric and PCM based BTMS. This study explores these emerging BTMS types, providing a comprehensive overview of their pros and cons. Additionally, the study examines the details of heat generation in li-ion batteries. The novelty of this paper lies in its focus on various studies of PCM-based BTMS, offering a thorough examination of the advantages and disadvantages of these approaches. Moreover, the discussion considers the practicality of incorporating such technologies into commercial EVs.

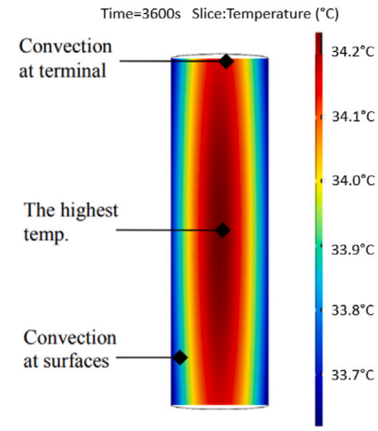


Fig. 1. Heat distribution of a 18 650 li-ion battery cell after 3600 s while being discharged at a rate of 0.5C [9].

2. Heat generation within the battery

In a li-ion cell, heat is produced as it charges and discharges. This heat is generated from its core and spreads outwards, influencing the overall performance and longevity if too much heat is generated. An example of the heat distribution within a li-ion Battery Cell is displayed in Fig. 1 [9]. Most cooling methods are only able to cool the cell at the surface level as cooling the li-ion cell from the core would involve altering the composition of the cell itself which in turn would reduce the compactness and efficiency of the battery.

The heat produced by the li-ion cell occurs through both Joule heating effects and reversible heat generation effects at the solid and electrolyte phases when charge is transported [6]. The rate of charging and discharging of the li-ion Battery Cell relative to its nominal capacity also has an effect on the heat generated by the battery whereby higher rates would lead to more heat dissipated by the battery [10]. This rate is defined as the C-rate. The equation used to model the heat generation in a li-ion Battery Cell is as displayed in Eq. (1) [11].

$$\dot{Q} = I(OCV - V) - I\left(T_{Bat}\frac{dOCV}{dT_{Bat}}\right) = \dot{Q}_{joule} + \dot{Q}_{entropy} \tag{1}$$

$\dot{Q}$ (W) is the heat generated by the battery, I (A) is the nominal current, OCV (V) is the open circuit voltage, V (V) is the nominal voltage, T_{Bat}(°C) is the battery's temperature and $\frac{dOCV}{dT_{Bat}}$ is the differential between the open circuit voltage and the battery's temperature. The first term in Eq. (1) represents the heat produced through Joule heating effects which is primarily caused as a result of electrical energy lost. The Joule heating equation can be alternatively expressed in terms of the internal resistance, R_{int} of the battery as in Eq. (2) [9].

$$\dot{Q}_{joule} = I(OCV - V) = I^2(R_{int}) \tag{2}$$

The second term in Eq. (1) represents the heat generated through entropy changes as electrochemical reactions occur. Heat generated through entropy is predominately higher at low discharge rates as compared to higher discharge rates [9]. Hence, the thermal impact of entropy heat is not as significant at high discharge rates. The entropy heat equation can be further expressed as in Eq. (3) [9].

$$\dot{Q}_{entropy} = -I\left(T_{Bat}\frac{dOCV}{dT_{Bat}}\right) = -IT_{Bat}\left(\frac{\Delta S}{nF}\right) \tag{3}$$

ΔS is the entropy change of the battery, n is the number of electrons transferred during discharge and F is the Faraday constant. Choudhari et al. [12] verified the accuracy of this equation by comparing a

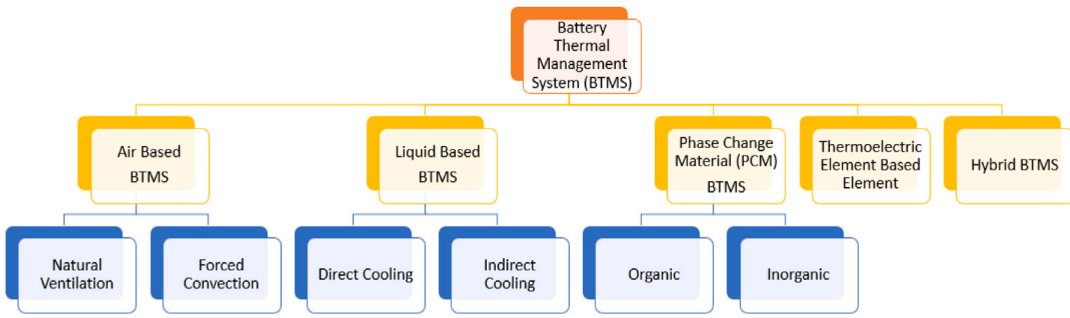


Fig. 2. Different BTMS types utilized for EV li-ion battery packs [15,16].

simulated battery heat generation model through computational fluid dynamics (CFD) with an experimental model under 3C, 3.5C and 4C discharge rates. Results from the accuracy verification test display near-identical temperature rise values between the experimental and CFD model thus verifying the adequacy of the mathematical model.

As standard EV battery packs are compact in nature, excessive heat generated from individual li-ion Battery Cells could affect the heat distribution and temperature uniformity inside the li-ion battery pack. In addition to the minimal space requirements of EV battery packs, such packs progressively require faster charge rates to increase their competitiveness against internal combustion engine vehicles which in turn would increase the cooling requirements of the pack [13]. Hence, the role of the BTMS is crucial in maintaining battery temperatures at optimal levels throughout the pack to prolong battery life and to mitigate fires and explosive hazards across the li-ion battery pack.

3. EV battery thermal management systems (BTMS)

The BTMS of an EV plays an important role in prolonging the li-ion battery pack's lifespan by optimizing the batteries operational temperature and reducing the risk of thermal runaway. There are several traits that a good BTMS should have which include maintaining the li-ion battery pack temperature between 15 °C - 35 °C, be light, compact and energy efficient, reasonably priced, even regulation of battery cell temperature throughout the pack and provide sufficient ventilation in the event that toxic fumes are leaked from a li-ion battery fire [6,14]. There are various BTMS types utilized in the automotive industry which include Air based, liquid based, PCM thermal management based, thermoelectric element based and hybrid systems. The sub-categories for each system are displayed in Fig. 2.

The most commonly used BTMS types in EVs are air and liquid-based cooling as the cooling capacity can be actively optimized based on the thermal load of the battery as compared to other passive cooling methods such as PCM and heat pipe BTMS types [8]. This optimization is crucial when there are large deviations in energy demand across the battery pack as heat produced by the battery is proportional to its energy demand. Air based BTMS utilizes air flow to convect heat away from the li-ion battery pack. It is divided into Natural Ventilation and Forced Convection systems. Heat distribution is controlled through the optimization of air-flow channels and cell array configurations in the li-ion battery pack. Liquid Based BTMS is separated into Direct and Indirect systems. Direct cooling involves the submersion of the li-ion battery pack in a dielectric coolant such as oils and engineered fluids to conduct heat away from the battery. Meanwhile, indirect cooling involves channeling a coolant through a medium such as a cooling plate with integrated tubing channels or looping a cooling ribbon across the battery pack to conduct heat away.

Passive cooling BTMS types have limited applications in EVs due to their constrained cooling capacity, which is effective only within a specific range of thermal loads. Consequently, EVs employing passive cooling are restricted to a singular charging profile and have limited acceleration to limit its power draw from the li-ion battery to avert excessive heat generation. Nonetheless, if the specific operational characteristics of the EV do not prioritize this functionality, adopting a passive cooling system becomes advantageous as an active power-consuming component, such as a pump or fan, is not needed. Examples of passive cooling BTMS include PCM and thermoelectric-based systems.

PCM based BTMS utilize materials that have high latent heat capacities to allow them to conduct large quantities of heat passively during their solid to liquid transition. As such, PCMs utilized for BTMSs have melting points within the optimal operating temperature of the li-ion battery pack. This will enable the PCM BTMS to effectively conduct and dissipate heat passively from the battery while maintaining favorable operating thermal conditions. There are two main types of PCMs, organic and inorganic. Organic PCMs are chemically stable, non-corrosive and have high latent heat capacities and have melting temperatures between 15 °C-130 °C. Their main weaknesses are their combustibility and poor thermal conductivity. There are several thermal conductivity enhancement techniques which include the addition of metallic fins or extended surfaces, incorporation of metal-based additives and installation of heat pipes [17,18]. Inorganic PCMs are non-combustible, have high latent heat energy, are good thermal conductors and have low thermal expansions. However, the melting temperature of inorganic PCMs are between the 307 °C to 380 °C and 700 °C to 900 °C range making them unsuitable as a BTMS for li-ion battery packs [19].

The thermoelectric element consists of a thermoelectric generator (TEG) and thermoelectric cooler (TEC). The TEG cools the li-ion battery pack by converting heat from the battery pack to electricity through the seeback effect while the TEC converts electricity to heat through the Peltier effect to warm the battery pack when needed [20]. There are hybrid BTMS between the other four BTMS types such as with air and liquid BTMS or PCM and airBTMS. Each BTMS has its own set of strengths and weaknesses, and the mitigation of these weaknesses is of great importance in improving the overall quality of the BTMS. As such, the methodology employed in this research involves reviewing the results and findings of studies on this topic and then providing an analysis on its limitations and how it may be improved further.

4. Air based BTMS

Air based BTMS have distinct benefits over liquid, PCM and thermoelectric based BTMS including the utilization of a direct, low risk, non-viscous coolant, is compact and lightweight in design, cost effective, requires low maintenance and has good reliability [21]. Active cooling BTMSs such as with thermoelectric thermal management and liquid based BTMS require additional energy to operate either the pump, TEG or TEC system resulting in reduced mileage of the EV [22]. However, this difference in efficiency is only applicable at low heat load conditions. At excessive heat load conditions such as with high charge and discharge rates or high ambient temperatures, Air based BTMSs consumes relatively more power than liquid and thermoelectric BTMS [23,24].

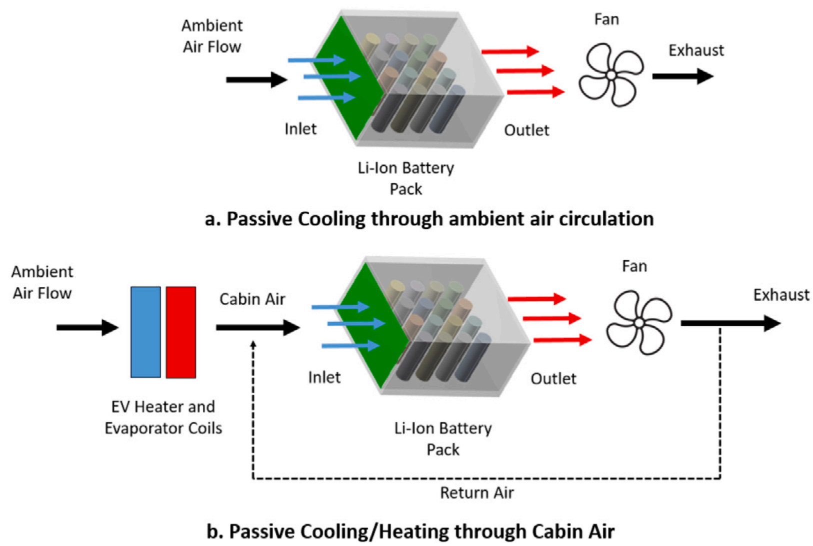


Fig. 3. (a) Passive air cooling through ambient air flow for li-ion battery packs (b) Passive air cooling/heating through cabin air flow [25].

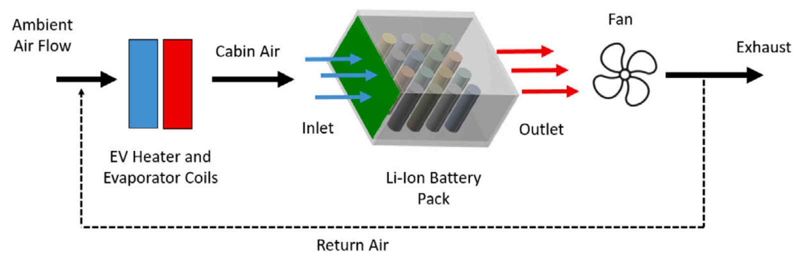


Fig. 4. Active Air Cooling/Heating design by incorporating fan/blower at outlet [25].

Similarly, PCM BTMSs are also more efficient than air based BTMS at high thermal loads [26]. However, most PCM BTMSs will be significantly heavier as large quantities of PCMs are required to ensure that the PCM Latent Heat capacity matches the heat produced by the li-ion battery pack [26]. Khateeb et al. [27] designed a Passive PCM BTMS for EVs and highlighted that the PCM in their design accounted for approximately 29% of the li-ion battery pack's total weight. Hence, air based BTMS are suitable for low heat load li-ion battery applications and is significantly lighter than other BTMS types. While many commercial EVs utilize liquid based BTMS for its li-ion battery packs, air based BTMS are also utilized in several low energy demand li-ion battery systems for EVs and hybrid EVs that are catered for the low-cost market and have less emphasis on fast charging or discharging capabilities [28]. Among the EVs and hybrid EVs that use air based BTMS includes the Honda Fit EV, Honda Insight, Nissan Leaf, Nissan e-NV 200, Hyundai IONIQ, Toyota Prius Prime, Renault Zoe, SAIC GM Wuling Hongguang and the Lexus UX300e [26,29].

4.1. Natural ventilation and forced convection

Air based BTMSs typically operate under two modes, natural ventilation and forced convection. When there is a low thermal load and the EV is moving, natural ventilation is achieved when the ambient air flows into the inlet of the li-ion battery pack through the motion of the vehicle and exits at the outlet [26]. The ambient air circulates through the gaps between the li-ion battery cells and dissipates heat away from the battery pack. This model is as displayed in Fig. 3(a). Another form of passive cooling involves redirecting air from the cabin to the battery pack as displayed in Fig. 3(b). Through additional ducting, the cooled cabin air can be directed to the battery pack to improve cooling performance. Such forms of cooling will not be sufficient if the vehicle is not moving at sufficient velocity, if the ambient temperature is too high or if the general thermal load of the battery is too high. The thermal gradient of the li-ion battery pack will be uneven which could lead to lower uniformity in charge or discharge rates across the battery pack [30]. To remedy this matter, additional fans or blowers are installed to better cool or warm the battery pack by increasing the air flow rate going across the battery system.

By controlling the fan or blower speeds at either the inlet or the outlet, the battery pack's temperature can be regulated based on the thermal load of the battery pack. An example of such a configuration is as displayed in Fig. 4. Additional ducting is installed from the fan or blower to go before the heater and evaporator coils of the EV to ensure greater air flow rates pass through the battery pack. Most air based BTMSs are stemmed from this design and research conducted towards the improvement of this model's performance can be divided into five categories which include the optimization of the li-ion Cell array distribution, optimizing the inlet and outlet of the designed pack, streamlining the cooling channels and the addition of thermally conductive enhancers [31].

4.2. Li-ion cell array distribution

Improving the battery pack architecture can be done by configuring the battery cell layout to maximize the heat dissipation rate from the battery while maintaining the lowest cost, occupy the least volume and possesses the highest energy density [31]. It should be noted that the optimal cell array layout is highly dependent on the application and design requirements of the battery pack [32]. Aditya et al. [33] conducted a forced convection study to determine the thermal performance of a 3×10, hexagonal and 6×5 arrangement of li-ion cells through a CFD model and later verified with an experimental study as displayed in Fig. 5.

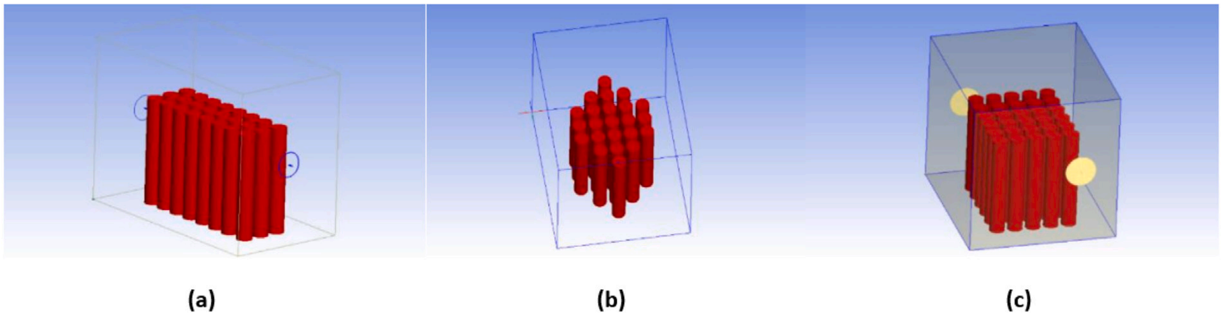


Fig. 5. Altering the li-ion cell arrangement to improve thermal convection of battery pack (a) 3 × 10 cell arrangement (b) hexagonal arrangement (c) 6X5 arrangement [33].

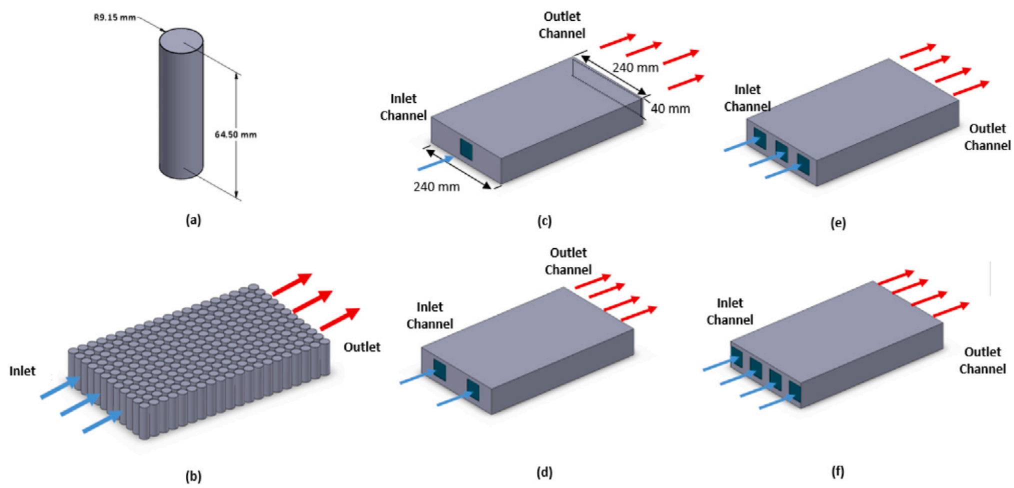


Fig. 6. Parametrization on the number of inlets for an air cooled battery pack (a) The dimensions of the 18650 li-ion cell used in the study (b) Two hundred and forty li-ion cells used in the simulation (c) Single inlet battery pack (d) Two inlet battery pack (e) Three inlet battery pack (f) Four inlet back inlet battery pack [34].

The airflow rate in the study was set at steady-state, laminar and incompressible flow condition while the battery's discharge rate was set as its nominal capacity. The results indicated a notable difference in heat convection between the hexagonal and the other rectangular configurations, with the hexagonal arrangement exhibiting superior thermal performance at higher wind velocities. This finding suggests that the arrangement of battery cells can significantly impact the convective heat dissipation, a crucial factor in battery thermal management. Furthermore, Yang et al. [35] conducted a similar study, investigating the effects of adjusting the longitudinal and transverse spacing in both aligned and staggered li-ion battery packs. The study involved a discharge rate of 2C with constant flow rates. The results demonstrated that an aligned array with a longitudinal and staggered distances of 34 mm and 32 mm, respectively proved to be the most optimal design. This configuration effectively minimized temperature rise, reduced power requirements, and improved temperature uniformity and cooling efficiency within the battery pack. The main limitation with the altercation of pack arrangement to better improve the temperature uniformity of the battery pack though is that it will affect the busbar arrangement of the battery while increasing the spacing between cells would affect pack density. A hexagonal arrangement of cells would limit the number of series and parallel busbar connections as the number of cells in the center column would be more as compared to the outer sections of the hexagonal arrangement. Increasing the longitudinal and transverse spacing of the cell or using a aligned arrangement would in turn increase the pack's volume which would decrease the pack's energy density. As such, altering the pack's arrangement should only be considered if spacing across the battery pack is not critical.

4.3. Optimization of inlet and outlet

Aside from altering the li-ion Cell array distribution, the optimization of the inlet and outlet of the battery pack is an alternative improvement strategy as it allows for the packs arrangement to remain the same while improving its cooling performance. Various methods were considered in improving the design of the inlet and outlet of an air cooled battery pack including revising the number of inlet and outlet points, adjusting the inlet cooling fan air temperature and configuring its position on the battery pack itself to maximize cooling rates. Widyantara et al. [34] analyzed the effects of increasing the number of inlets and the inlet's air temperature of an air cooled li-ion battery pack with an outlet of fixed dimensions through CFD simulation as displayed in Fig. 6. The li-ion Cell used in the battery pack is a standard 18650 cell that is 18.3 mm in diameter, 64.5 mm in height, nominal capacity of 2.6 Ah and nominal voltage of 3.7 V as displayed in Fig. 6(a).

The battery pack consisted of two hundred and forty li-ion battery cells and has a width of 240 mm as indicated in Fig. 6(b). Each inlet is 40 mm X 40 mm while the outlet is 240 mm X 40 mm. Models of the battery pack with 1, 2, 3 and 4 inlets are as constructed in Fig. 6(c), (d), (e) and (f) respectively. Each li-ion Battery cell is modeled to be discharged at 1C, the airflow velocity at each inlet was set at 1.4 m/s, the outlet pressure is 0 MPa and the ambient temperature was set at 30 °C. Results from the study display that beyond three inlet points, the maximum temperature rise of the li-ion cell was not significant which would indicate that there is an optimal number of inlet points for an air cooled BTMS. The study conducted was based on a discharge rate of 1C so battery packs catered for higher discharge rates might require more inlet points to maintain optimal temperatures. Widyantara et al. [34]

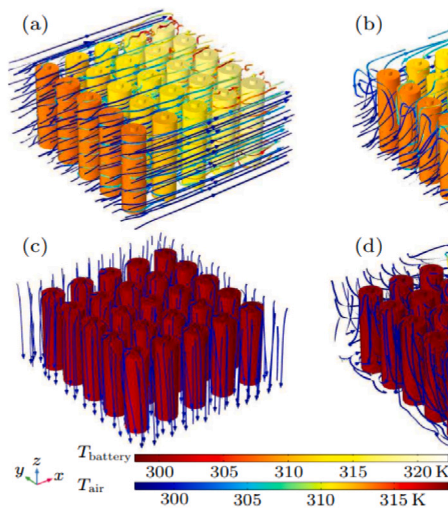


Fig. 7. Adjustment of inlet and outflow position in a battery pack (a) Left side inlet and right side outlet (b) Lower left half side inlet and upper right side outlet (c) Top side inlet and bottom side outlet (d) Upper left half side inlet and lower right side outlet [36].

also highlighted that lowering the inlet air temperature had a more significant impact in reducing the li-ion Battery's operating temperature than adjusting the number of cooling fan inlets.However, colder inlet air temperatures require more power from the air conditioning unit which would also reduce the overall efficiency of the li-ion battery pack. Hence, it is imperative that the number of cooling fan inlets and the conditioned inlet air temperature be fine-tuned to the operating ambient temperature and size of the battery pack itself.

Du et al. [36] simulated the cooling effectiveness of adjusting the fans at different inlet and outlet points in the battery pack as displayed in Fig. 7. In the simulation, four conditions were set. Fig. 7(a) has the inlet at the left side while the outlet is set at the right side, Fig. 7(b) has the inlet at the lower left half and an outlet at the upper right side, Fig. 7(c) has the inlet at the top side and the outlet at the bottom side and Fig. 7(d) has the inlet and the upper left side and the outlet at the bottom right side. Results from the simulation display that the maximum temperature rise of the battery closest to the inlet was the lowest while the temperature of the battery in the middle and closest to the outlet has the higher temperature rise. Additionally, the inlet and outlet arrangement of Fig. 7(c) has the lowest temperature rise among the other models. It can be deduced that a vertical air cooling strategy is the most effective method of positioning the inlet and outlet of an air cooled battery pack. However, a vertical air cooling strategy might not be feasible for several EV types as it would increase the vertical height of the battery pack due to the installation of vertically inclined inlet and outlet manifolds. Hence, a vertical cooling strategy may only be feasible for EV types that have substantial vertical clearance.

4.4. Streamlining cooling channels

The other parameter to be considered is the cooling channel leading up to the inlet and exiting the outlet. For an air cooled battery system, increasing the cooling channel's size would improve the cooling efficiency of the system but would decrease the cooling uniformity of the system [37]. Aside from the size of the cooling channel, its geometrical configuration also attributes to the cooling effectiveness of the air cooled BTMS. There are three main cooling channel configurations developed which include the Z, U and J type cooling channel structure. Each of the cooling channel configurations is able to control the li-ion battery's maximum temperature rise at specific temperature ranges and each structure has its advantages and weaknesses [38].

Zhang et al. [39] analyzed the effectiveness of a Z Type air based BTMS with secondary cooling outlets as shown in Fig. 8(a). CFD simulation was done firstly through the ANSYS ICEM software and then validated through an experimental model. The study compared the effectiveness of varying the number of secondary outlets as compared to a z-type air cooled BTMS without these outlets. The primary inlet and outlet were set with a width of 20 mm and a length of 70 mm. The battery used in the model is a li-ion battery with a length of 65 mm, width of 18 mm and a height of 140 mm as displayed in Fig. 8(b). The heat generation model of the li-ion battery is based on discharge rates between 0.5C to 2.5C with 0.5C increments while the air inlet velocity was set at 3.0 m/s and 3.5 m/s to ensure results accuracy. The Z-type air BTMS with secondary outlets are modeled with different number of outlets up to a maximum of 8 while the base model does not have the secondary cooling outlets and is used as a comparison. Results from the study indicated that when there are six secondary outlets along the outlet channel reduced the maximum temperature rise of the li-ion battery by 2.8% as compared to the base model. This indicates that the addition of a secondary outlet point along the outlet channel would improve the thermal efficiency of such a battery pack.

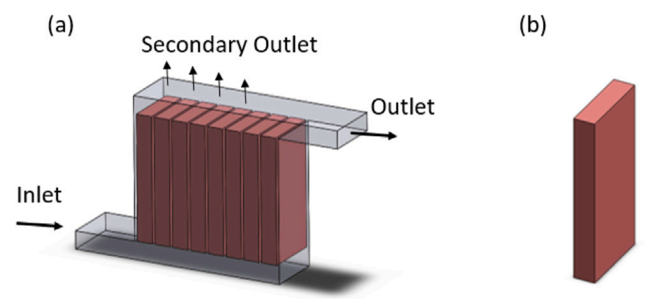


Fig. 8. Z Type Air Cooling BTMS system with secondary cooling channel proposed by Zhang et al. (a) Flat plate li-ion battery cells positioned at the center of the Z type air cooled BTMS (b) li-ion cell with a dimension of 65 mm in length, 18 mm in width and 140 mm in height [39].

Wang et al. [40] improvised on the existing Z-type air cooling structure by analyzing the effects of adding different spoiler geometries across the battery gap spacing to improve its air cooling uniformity and effectiveness through CFD as displayed in Fig. 9. The different spoiler geometries analyzed included a straight, parabolic and arc spoiler as displayed in Fig. 9(a), (b), (c) respectively. The cooling performance of the Z-type spoiler air cooling BTMS was compared with a standard Z-type cooled air BTMS to determine its overall effectiveness. Results from the CFD model indicate that the spoilers reduce the battery's maximum temperature, change the airflow path and improve

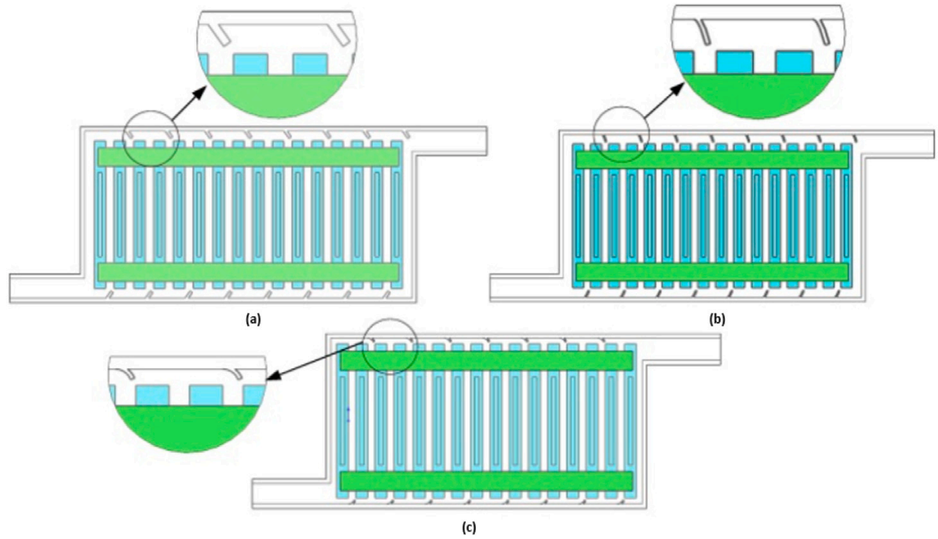


Fig. 9. Z-Shaped air cooling BTMS structure with different geometrical spoilers between gaps to improve air cooling uniformity (a) Straight spoiler (b) Parabolic spoiler (c) Arc spoiler [40].

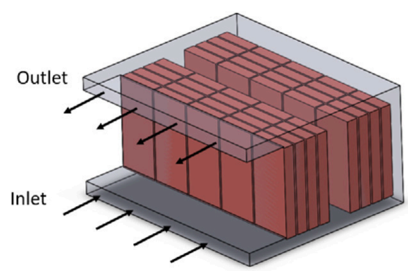


Fig. 10. Parallel U-Type Air Cooling proposed by Chen et al. [41].

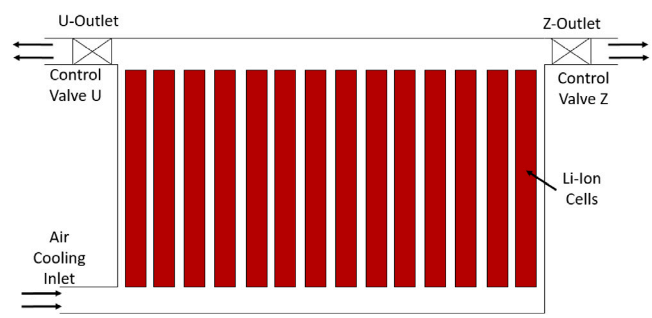


Fig. 11. J-type air cooling structure with U-Outlet and Z-Outlet outfitted with its respective control valves [42].

on the battery's temperature uniformity. The straight spoilers were also determined to reduce the battery's maximum temperature the most.

Chen et al. [41] developed a parallel cooled U-type air cooling system through a flow resistance network model as seen in Fig. 9. The model developed was optimized to improve the uniformity of the cooling channel's airflow rate by adjusting the angles of the plenums and the optimized model is compared with a standard Z-type air cooling structure without additional outlets. The inlet and outlet of the cooling system face the same direction and the li-ion cells modeled are 65 mm X 16 mm X 151 mm in dimension. Spacing between the li-ion cells is 3 mm, the inlet and outlet width are both 20 mm respectively, inflow airflow rate is set at 0.012 m^3/s and initial inlet temperatures are set at 26.85 °C. Results from the study show that the optimized U-type air cooling system had 33% lower temperature differences at a discharge rate of 5C. Hence, it can be determined that the U-type air cooling structure also improves temperature uniformity for air cooled systems similar to the effects of including secondary outlets (see Fig. 10).

U and Z type air cooling structures have a common weakness which is that they only work under stable operating temperatures. Both systems are not able to effectively regulate battery temperatures for rapid temperature rises caused by fast charging and discharging of the battery [38]. As such, the J-type model which is an adaptation of both the U and Z type cooling system is designed to remedy this issue. Essentially, the J-type air cooling structure has two outlets with control valves which would control the opening angle to better regulate the airflow passing through the li-ion battery pack as shown in Fig. 11.

Liu et al. [42] conducted a parametric comparison between the U, Z and J type air cooling models through the surrogate-based optimization method. Discharge rates of the battery was incrementally increased from 1C to 3C discharge rates. From the study, it was determined that at high heat generation rates, the J type air cooling system was able to better perform than the U and Z type cooling system. Whereby the maximum battery temperature rise of the J type cooling system was the lowest compared to the U and Z type. Hence, a J-type air cooling structure, capable of transitioning between U and Z type modes based on EV operating conditions would be optimal for an air cooled BTMS. It should be noted that such an enhancement may increase the complexity of the ducting infrastructure within the EV which would not be suitable in compact EV models. Therefore alternative enhancement methods that do not compromise the complexity of the battery pack would be more appropriate for small EVs.

4.5. *Thermal conductivity enhancers*

An alternative to altering ducting configurations is through the implementation of thermal conductivity enhancement measures in the battery pack itself. Saw et al. [43] introduced an air-cooled battery pack with porous aluminum foam wedged between li-ion pouch cells to function as cooling plates as displayed in Fig. 12. A limitation of traditional air cooled BTMSs is that the air medium absorbs heat as it flows along the battery pack leading to the outflow air being hotter than the inflow air which reduces cooling uniformity across the battery pack. The addition of porous aluminum foam cooling plates allows for better cooling distribution with little flow resistance. Results from the design implemented by Saw et al. [43] indicated that a 10 parts per inch

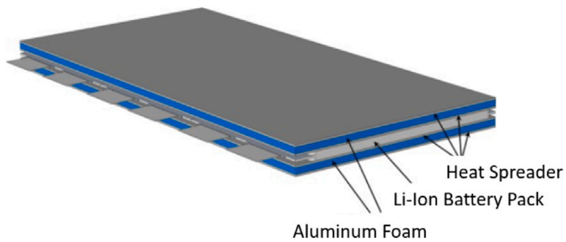


Fig. 12. Aluminum foam wedged between li-ion pouch cell to function as cooling plates [43].

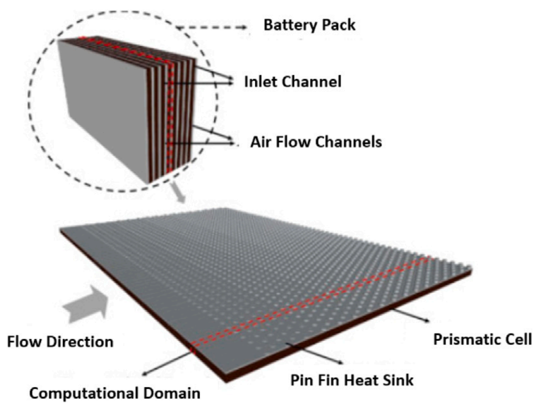


Fig. 13. Aluminum pin fin heat sinks attached between prismatic li-ion cells to improve cooling uniformity across the battery pack [44].

aluminum foam structure at 91.9% porosity offered the best cooling performance.

Similarly, Mohammadian et al. [44] introduced pin fin heat sinks between li-ion prismatic cells to improve the cooling distribution across the li-ion battery pack as shown in Fig. 13. In the study conducted, eight 15 Ah Prismatic Cells are fitted with pin fin heat sinks and six different variations were modeled with model 1 as just a heat sink design to be used as a reference to the effectiveness of the fins. The batteries are discharged at varying discharge rates which include 1C, 2C, 3C, 4C and 5C with a thermal model of each pin fin battery pack modeled through CFD. Each pin-fin heat sink model consists of eighteen pin fins with the fin height increased gradually from the shortest at the inlet and the tallest at the outlet.

Each model excluding model 1, has different increments in pin-fin height to best optimize the battery pack in terms of cooling uniformity and reduction in maximum battery temperature rise. Results from the CFD analysis displayed that the pin finned design had overall lower temperatures and better temperature uniformity than the purely heat sink design. Furthermore, the model that left the first four pins at 0 mm then a gradual increment of 0.3 mm after every five pins had the greatest temperature uniformity. Temperature uniformity across the pin finned battery pack was improved by increasing inlet air temperatures but would simultaneously increase maximum battery temperature rise while increasing the airflow velocity would decrease the batteries maximum temperature but would reduce temperature uniformity. As such, the optimal inlet air temperature and velocity for a pin-finned battery pack would vary depending on the size of the battery pack.

Aside from its thermal conductivity enhancing capabilities, an added advantage to the addition of cooling fins is the added improvement to its structural strength against impact. When li-ion batteries are subjected to mechanical deformation, the risk of an internal short circuit increases which in turn could lead to thermal runaway, combustion, or explosions [45]. Hence, li-ion battery packs have to be designed to be protected against mechanical damage while also being able to dissipate heat effectively. Shi et al. [46] investigated the effects of optimizing the cooling fin's geometry between the li-ion pouch cells to determine the effectiveness of the cooling fins in reducing the impact force on the cells under a simulated impact test.

Results from the analysis have displayed that the cooling fins are able to absorb a substantial amount of impact energy and that a unidirectionally stiffened double hull structure and a circular core structure were able to absorb substantially greater impact energy and reduce peak force as compared to other fin configurations. Optimization of the fin heat sinks for both structural strength and thermal performance is difficult though as the parameters for both target criteria differ greatly.

The main issue with the addition of such thermal conductivity enhancers is their impact on the overall weight of the battery pack. The incorporation of porous aluminum foams, pin fin heat sinks, or supplementary cooling fins can indeed improve cooling uniformity but would increase the total weight of the battery pack. As such, this limitation should be considered in the overall design of the EV.

5. Liquid based BTMS

The main benefit of a liquid based BTMS is that it is able to achieve higher heat transfer rates with lower flow rates than air cooled systems [47]. Numerous types of fluids are used as coolants for liquid based BTMS including water, oils, water with suspended metallic particles and ethylene glycol [48]. As each fluid type has different viscosity and specific heat capacity values, the selected fluid type is dependent on the amount of heat needed to be absorbed as well as the mechanical energy required to channel the fluid around the battery pack. Liquid based BTMS is divided into two categories which are indirect and direct cooling with the main difference being that indirect cooling requires the coolant to be physically separated from the li-ion battery while the latter may be in full contact.

Indirect liquid cooling involves channeling a coolant through a cooling medium that allows a fluid to absorb the heat away from the battery pack while preventing a short circuit from occurring between the liquid medium and the li-ion battery pack itself. Some commonly used indirect cooling methods include cooling plates, thermally conductive tubing or through a heat pipe to conduct heat away from the li-ion battery pack.

5.1. Cooling plate channel optimization

The cooling plate liquid BTMS is a flat plate with internal cooling channels and it is mostly suited for prismatic cells. There are two primary parameters to be considered in improving the cooling effectiveness of the cooling plate which are the position of the plate and the channel configuration within the plate itself [48]. The cooling plate can be placed at three locations in the battery pack including the side of the battery pack [49], in between adjacent li-ion cells [50] and internally within the li-ion cell [51] as seen in Fig. 14(a), (b) and (c) respectively.

As the electrical terminals and batteries busbar are positioned at the top of the battery pack, the side cooling plates are positioned on either the horizontal sides of the battery pack or the bottom of the pack. Additional heat spreaders are attached between the adjacent li-ion cells to channel heat from the inner sections of the battery pack to the cooling plate. Adding the cooling plates between the adjacent li-ion cells would greatly improve the cooling effectiveness at the center of each li-ion cell but would require the li-ion cell to be thinner in order for the cooling plates to be effective. For the internal cooling plate to be integrated inside the battery pack, the cooling channels have to be sufficiently small to be placed inside a component of the battery such as with the current collector while having chemically inert channel walls [51]. While the internal cooling plate is able to bring the inner temperatures of the battery lower than the external cooling plates, such systems are much more intricate in design which would affect the manufacturability of such a cooling system.

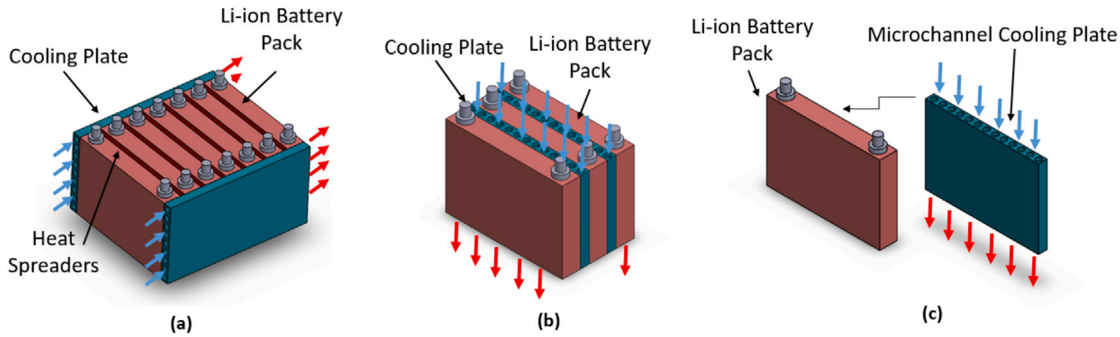


Fig. 14. Liquid cooling through the cooling plate (a) Battery module side cooling plate (b) Between li-ion cells (c) Micro-channel cooling plate inside li-ion Cell [52].

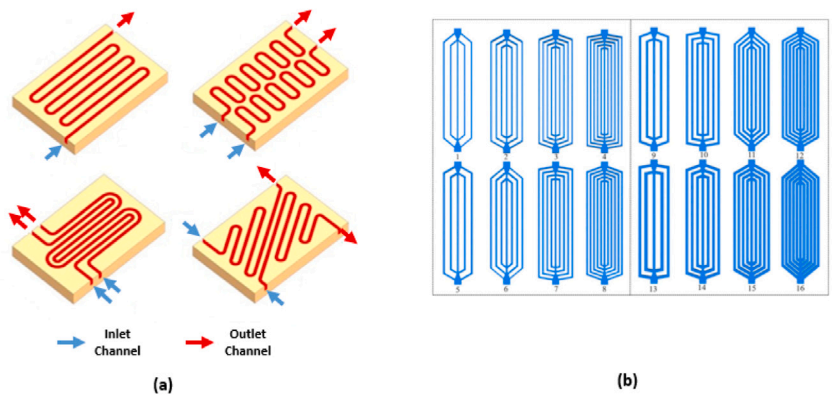


Fig. 15. Different liquid cooling channel configurations across cooling plates (a) Serpentine cooling channel (b) Parallel cooling channel inspired by spider-web design [54,55].

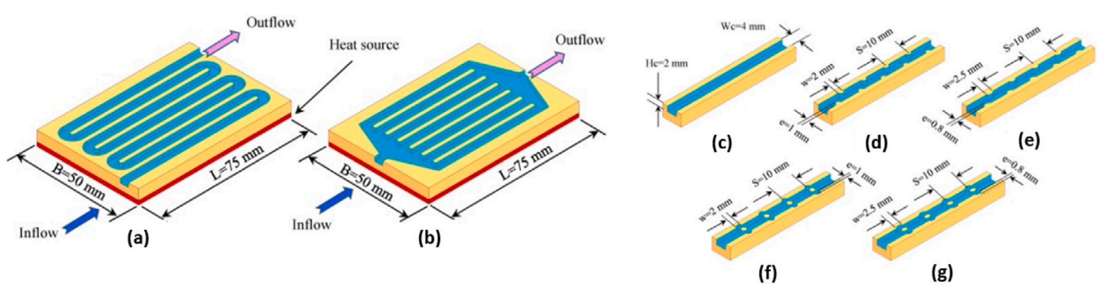


Fig. 16. Comparison between the effectiveness of serpentine and parallel cooling plate design and the effectiveness of varying groove patterns along the channel (a) Serpentine cooling plate (b) Parallel cooling plate (c) Standard straight channel (d) Semi-circular grooves (e) Circular grooves (f) Circular fins and grooves (g) Elliptical fins and grooves [56].

The channel configuration is also correlated to the cooling performance of the cold plate as it determines the heat transfer area and pressure drop of the cold plates. Various design variables including the number of channels, channel width, channel height, inlet velocity, and fin width along with inlet and outlet positions factor into the thermal effectiveness and equivalent pressure drop of the cooling channel [53]. Furthermore, there are two main cooling channel configuration types which are serpentine and parallel-shaped channels as displayed in Fig. 15. Imran et al. [54] investigated the effects of varying serpentine cooling channel configurations as displayed in Fig. 15(a).

Each cooling plate is subjected to laminar single-phase flow rates and the heat source applied was constant. Results from the analysis indicated that the serpentine design with two inlet channels had lowered the temperature profile of the cooling plate greater than the serpentine channels with only one inlet channel. However, increased number of inlet channels would require more pumps which would increase the power consumption of the liquid BTMS. Xie et al. [57] studied the effects of altering micro-channel sizes and have determined that a deep and narrow channel has better heat transfer rates than wide and shallow channel sizes. Wang et al. considered the effects of increasing the number of parallel cooling channels, increasing the width size while maintaining constant depth and altering the channel angles in a spiderweb-like design to determine which parameter affected the thermal performance of the cooling plate as displayed in Fig. 15(b). It was determined that increasing the channel width had the most significant effect on lowering the maximum temperature rise on the battery pack followed by increasing the number of channels. Altering the angles of the parallel cooling channels had little effect on the cooling effectiveness of the battery pack.

Mahmoud et al. [56] compared the differences in thermal performance of serpentine and parallel cooling channels while also determining the effect of the addition of pin fins with grooves along the sides of the cooling channels as displayed in Fig. 16. Results from the study show that serpentine cooling channels have better cooling uniformity with higher pressure drops while parallel cooling channels have the least cooling uniformity and low-pressure drops. The addition of grooves also increased the convective heat transfer rate while simultaneously decreasing the thermal resistance of the cooling plate with the most effective structure for the serpentine model having circular fins and grooves while the parallel model operates best with the elliptical fins and grooves as displayed in Fig. 16(f) and (g) respectively.

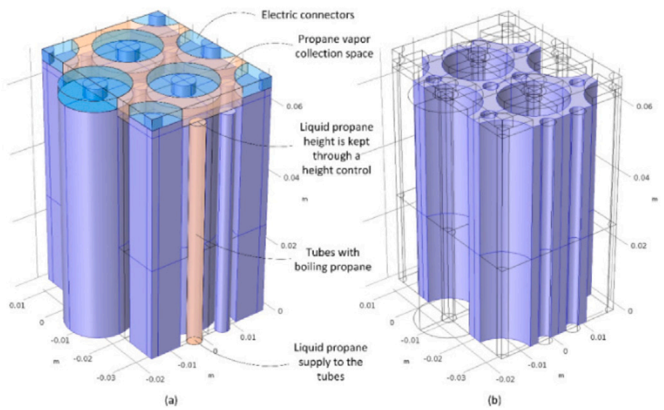


Fig. 17. Cooling tube passes through an aluminum block and is absorbed by the latent heat capacity of liquid–vapor propane coolant (a) battery pack with liquid–vapor propane cooling system (b) Aluminum housing of cooling system [58].

Hence, it can be deduced that a cooling plate design with multiple inlet and outlet points constructed in a serpentine configuration with circular grooves and fins would provide the most optimal cooling output for prismatic and pouch li-ion battery packs. Considerations should also be made for the manufacturability and cost-effectiveness of the design as it is dependent on the size of the li-ion battery pack.

5.2. Thermally conductive tubing

Cooling plates may not be suitable for cylindrical li-ion cells as there are no flat surfaces to mount the cooling plates onto. As such, thermally conductive tubing works as a suitable alternative to cooling plates as liquid coolant filled tubing can fit through the narrow gaps between cylindrical cells while effectively conducting heat away from the li-ion cells. The Tesla Model S channels liquid coolant through a thermally conductive aluminum cooling tube coated with a dielectric material that is packed between each cylindrical li-ion cell to maximize the heat dissipation throughout the battery pack and is designed with a counter-flow element to achieve better cooling uniformity throughout the battery pack [28]. Al-Zareer et al. [58] constructed an aluminum housing with cooling tubes between cylindrical li-ion cells as displayed in Fig. 17.

The cooling tubes are filled with boiling propane that absorbs heat through the latent heat capacity available through the liquid to vapor transition. The pressure of the tubes are adjusted to 10 bar to achieve a boiling temperature of 26.94 °C which corresponds to the optimal operating temperature of the li-ion cells. A CFD thermal model of the system was conducted in which the battery pack was discharged at a rate of 6C and the results are compared with values from other studies that have a similar battery pack in submerged in liquid propane. Results from the CFD model indicated that the temperature difference of the li-ion cell for the constructed cooling system had lower temperature differences but had higher maximum temperature values than a direct liquid propane cooling system which would infer that the constructed cooling system allows for better cooling uniformity but not as effective for battery packs that operate under high charge and discharge rates.

Liu et al. [59] constructed a similar cooling system to analyze the effects of passing a vertical and horizontal cooling tube through an aluminum frame to cool cylindrical li-ion cells as displayed in Fig. 18. The effects of gradually increasing the gradient diameter of the tube and the effects of increasing the flow diameter of the coolant is also studied to determine its cooling effectiveness on the li-ion cell. Results from the study displayed that when the vertical tubing model was applied, the overall weight and volume of the cooling system needed was lowered by 19.50% and 12.26% respectively. In addition, the model in which the gradient diameter and gradient velocity were incrementally increased had lower li-ion battery temperature differences than the constructed model with constant diameter and flow velocity. Hence, when implementing such discrete tubing to cool li-ion battery packs, an aluminum housing with vertical tubing with increasing gradient diameter and flow velocities offers the best li-ion cooling in terms of lowering the battery's maximum temperature and with the best cooling uniformity.

5.3. Heat pipe condenser arrangement

Heat pipes (HP)s are heat transfer devices that are compact, adjustable in geometry and are used as thermal management devices for several applications including power electronics cooling and air conditioning systems [60]. HPs are filled with a heat transfer fluid and is divided into three zones which are the evaporation, adiabatic and condensation zone as indicated in Fig. 19. The battery system or heat source is attached to the evaporator section which would lead to the evaporation of the heat transfer fluid. The converted vapor will transfer heat to the condensation zone, converted back to a fluid, absorbed again in the wick micro-structure and then passively flowed back to the evaporation zone to repeat the process [61]. For BTMS applications, certain elements of the HP should be altered to match the cooling requirements of the li-ion battery pack which would include the heat transfer fluid used, cooling methodology at the condenser section and the geometry of the HP [52].

Behi et al. [63] constructed a HP structure for prismatic lithium-titanate cells as displayed in Fig. 20. The protruding HP section is the condenser section while the portion attached to the battery pack is the evaporator section. The capacity of the cell is 23Ah, each heat pipe is 250 mm × 11.2 mm × 3.5 mm (length × height × width) in dimensions and the cells were discharged at a rate of 8C. The maximum temperature rise of the prismatic li-ion cell without the HP is compared with the cell attached with the HP under both natural and forced convection. Results from the experiment showed that the HP lowered cell temperatures by 13.7% and 33.4% respectively. While the HP system does manage to effectively reduce the maximum temperature rise of the battery, the condenser section has to be sufficiently extended beyond the length of the li-ion cell to be cooled which would dramatically increase the overall volume required of the BTMS system.

To resolve the space limitation and improve on the performance of the HP cooling system, Tran et al. [64] angled the condenser section, added aluminum fins to the condenser and introduced a chimney for additional cooling as displayed in Fig. 21. The evaporator section is attached to copper plates and acted as cooling walls for the li-ion cells, 14 cylindrical li-ion cells were used which had 6.5Ah capacities are 38 mm in diameter and 142 mm in height while the li-ion battery pack was discharged at 10C and 12C. The li-ion battery pack with angled HP is then discharged under natural convection, forced convection through an air chimney ventilation, that is both horizontally and vertically orientated.

It was determined that at such high discharge rates, the HP BTMS was not able to maintain the battery pack between the optimal temperature range between 15 °C to 35 °C but the forced convection model with air chimney ventilation was able to maintain the operational temperature of the battery pack at such levels. The angled HP was able to carry heat away from the battery pack when the pack is orientated vertically and when the pack was inclined up to a gradient of both −20° and +20°. However, when the battery pack was placed horizontally, the air flow from the ventilation was not able to carry heat away from the li-ion battery pack. Low ventilation rates are sufficient as increasing the air velocity does not significantly improve the cooling performance of the battery pack. While the overall design of the angled HP design is more compact than Behi *et al.'s* [63] design, the additional air chimney ventilation does still occupy a significant volume which might not be suited for compact EV vehicles.

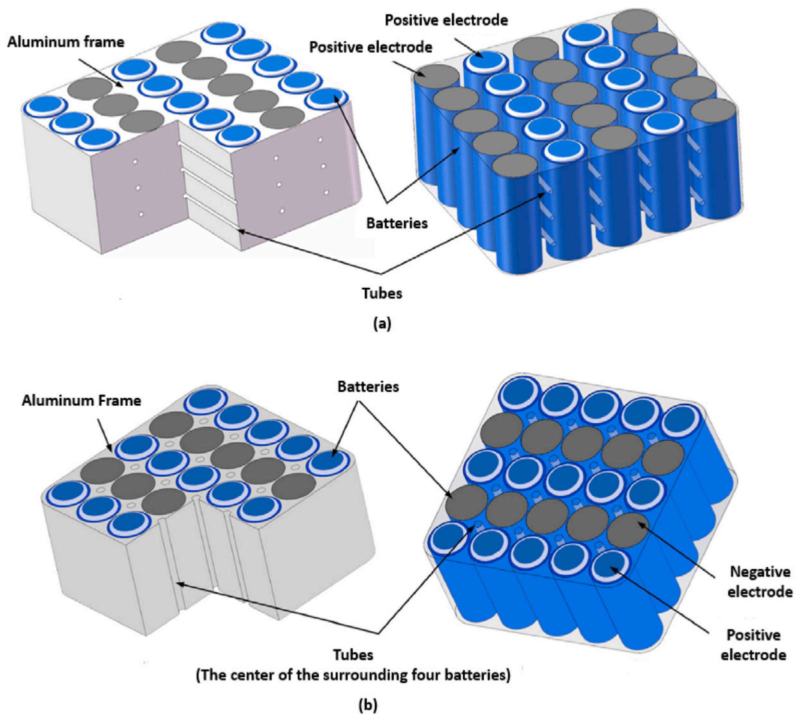


Fig. 18. Thermally conductive tubing passed through aluminum frame both vertically and horizontally to cool cylindrical li-ion battery pack (a) Horizontal cooling tubes passed through aluminum cooling frame (b) Vertical cooling tube passed through aluminum cooling frame [59].

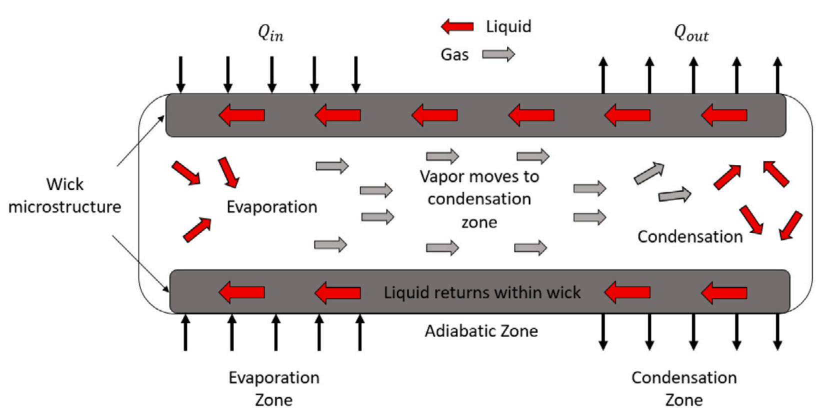


Fig. 19. Operating principle of HPs [62].

5.4. Direct cooling

Most liquid BTMS utilized for EVs are through indirect cooling methods and to dissipate the high heat loads from the li-ion battery packs, thermally conductive fluids with high heat capacities such as with water glycol and refrigerants are used across such systems [49]. The main weakness of such fluids for liquid BTMS applications is that they are electrically conductive and have to be physically separated through a thermally conductive medium from the main heat source which are the li-ion cells [65].

The addition of the thermally conductive medium increases the overall weight of the battery pack and the thermal resistivity of the cooling system which would in turn reduce the cooling efficiency of the liquid BTMS [66]. As such, direct cooling was a considerable alternative as such a cooling method maximizes the surface area being cooled, provides excellent cooling uniformity, reduces system complexity and increases the cooling capacity of the battery pack which would significantly increase the cooling efficiency of the battery pack [67,68]. Direct liquid cooling involves immersing the li-ion battery pack in a non-electrically conductive dielectric fluid with high specific heat capacities to cool the battery. Various dielectric fluids are used for immersion cooling but the most common types are deionized water, silicon oils, mineral oils and fluorinated hydrocarbons [68,69]. There is continuous research on developing better immersion fluids aside from the common types. For instance, Khan et al. [70] explored the effects of using supercritical CO_2 to cool a 20 × 5 battery energy storage system. When compared with other coolant types, the supercritical CO_2 had better temperature suppression and uniformity even at high discharge rates.

Immersion cooling fluids utilized for BTMS applications have high flash points and are non-volatile in nature which reduces the risk of thermal runaway in the battery pack [71]. Examples of EV battery companies that have adopted immersion cooling are Xing Mobility which have immersed their modular li-ion cells in 3M's Novec fluid, Rimac Automobile which have utilized Solvay Galden's fluid for their electric super-car applications and Kreisel adopting Shell's thermal management fluid [72,73]. There are various parameters that influence

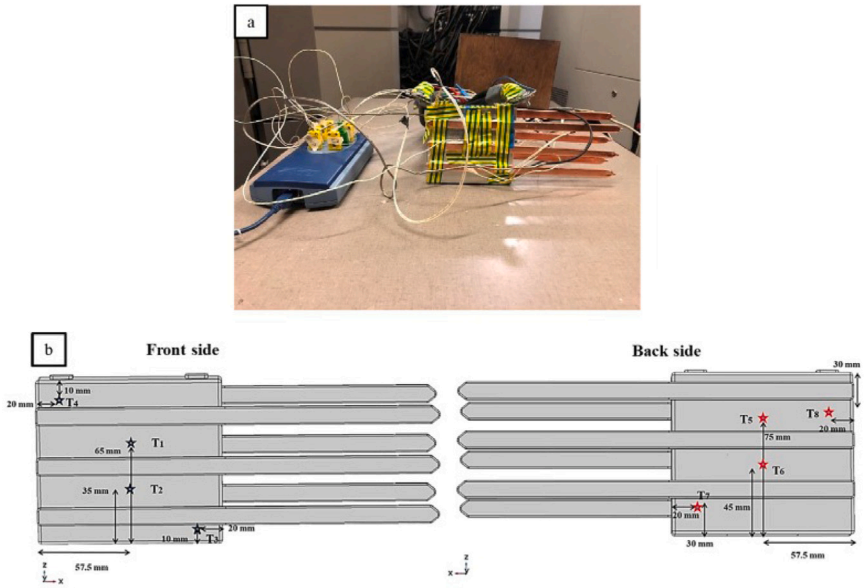


Fig. 20. HP design appropriated for prismatic lithium-titanate cell (a) Lithium-titanite cell with 6 flat heat pipes attached at both sides (b) Schematic diagram of the HP for the prismatic cell [63].

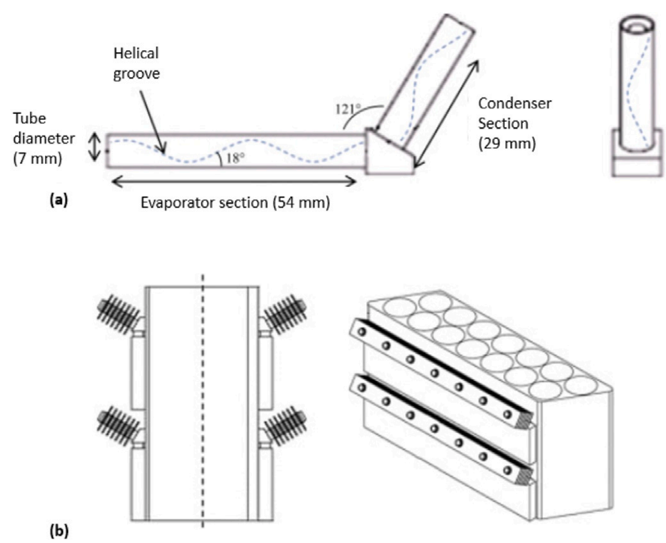


Fig. 21. Angled HP design to reduce spacial volume of battery pack (a) Evaporator section slotted inside li-ion battery pack with angled condenser section (b) Overall diagram of angled HP li-ion battery pack with aluminum fins [64].

the effectiveness of immersion cooling including the submersion level, flow type and the modes of cooling as displayed in Fig. 22 [68].

Immersion cooling is divided into two modes which are single-phase cooling and two-phase cooling. With single-phase cooling, the coolant remains in a liquid form and gets pumped through a heat exchanger as displayed in Fig. 23(a). Two-phase cooling involves utilizing a coolant with low boiling temperatures to vaporize the coolant and its vapor cooled back to liquid form through a water condenser unit as displayed in Fig. 23. The latent heat of vaporization during the liquid to vapor transition of a two-phase system improves the convective heat transfer significantly but in terms of EV BTMS applications there are several drawbacks as compared to the single-phase system [68]. Such disadvantage includes gradual loss of coolant fluid due to inefficiencies of the condenser unit, increased system complexity, higher maintenance cost, increased system volume and risk of coolant vapor contamination to the other electronic components at the undercarriage of the EV.

As such, for EV applications a single-phase immersion cooled battery pack are preferred over two-phase immersion packs due to its ease of maintenance and relatively lower costs. Despite the exceptional cooling performance of immersion cooling, there are several general weaknesses for immersion cooling which include the high viscosity of such fluids which increases the pump power required, such dielectric fluids are costly which would increase the general cost of the battery pack and the additional fluid would increase the weight of the battery pack. Hence, immersion cooled BTMS is better suited towards battery packs designed for fast charging and discharging requirements.

6. PCM thermal management BTMS

The high latent heat capacity that phase change materials (PCM) have allows PCM based BTMS systems to absorb large quantities of heat while being maintained at a constant temperature range without active energy consuming components such as fans or pumps. This in turn allows PCM based BTMS systems to be more efficient than air and liquid based BTMS due to the lack of parasitical power being drained from the battery pack. There are generally two types of PCMs which

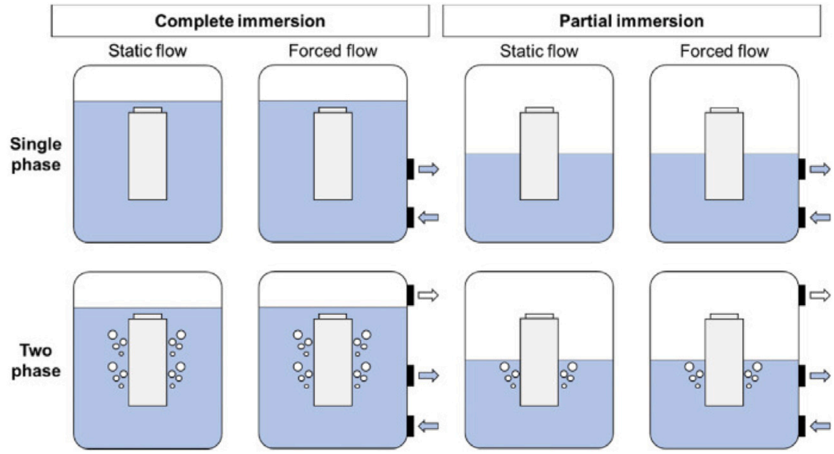


Fig. 22. Varying types of immersion cooling configurations for liquid BTMS applications [68].

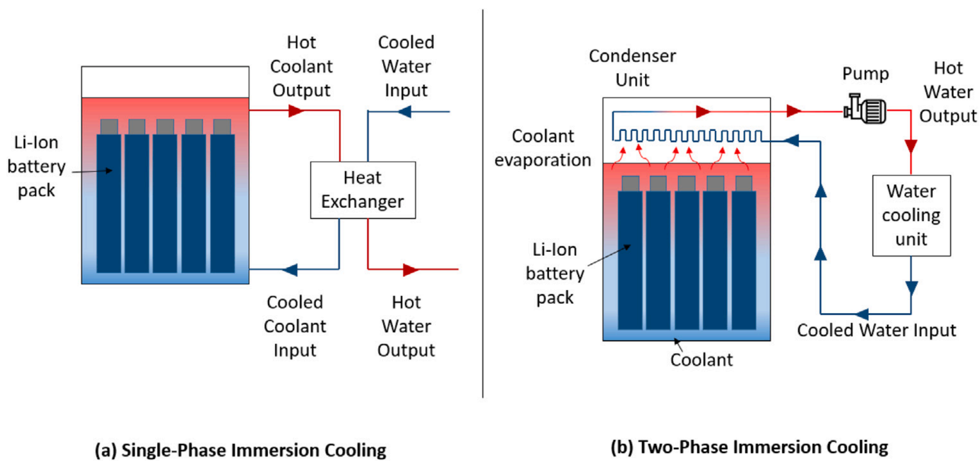


Fig. 23. Single-phase and Two-phase immersion cooling (a) Single-phase Immersion cooling utilizing heat exchanger (b) Two-Phase Immersion cooling that involves evaporation of coolant and condenser unit to convert vapor coolant back to liquid form [74].

are organic and inorganic based PCMs each with their own distinct chemical and thermal properties.

Organic PCMs are further divided into two categories which are paraffins and non-paraffins such as with fatty acids, glycols and sugar alcohols [75]. Organic PCMs have several advantages which allow them to be better suited for EV BTMS applications which include being non-corrosive, non-toxic and chemically stable. However, organic PCMs have low thermal conductivity, are combustible which would be hazardous in the event of thermal runaway and is less viscous as compared to inorganic PCMS which would increase the risk of the PCM leaking through the container during the solid to liquid phase transition [76]. There are various methods to improve the thermal conductivity of organic PCMs but there are generally three methods which include the addition of fins, encapsulating the PCM in a thermally conductive coating and the addition of thermally conductive fillers such as with graphite nano-particles and metallic foams [77].

6.1. PCM fin configuration

The installation of fins across the PCM's container is an effective method in improving the heat transfer of organic PCMs as the structure is easily manufactured while being able to significantly improve the thermal conductivity of the PCM [78]. There are two main methods of installing the fins which are placing the fins directly into the PCM compound and the other to place the fins on top of the surface of the PCM to be then cooled separately through air cooling [76]. The thermal conductivity performance of the fins are influenced by several factors including the fin material used, length, number of fins and its structure [79].

Weng et al. [7] investigated both the effects of implementing varying fin configurations and adjusting the number of fins across the container on its ability to enhance the thermal conductivity of PCMs and compared the results with a purely PCM system as displayed in Fig. 24.

The experiment was conducted with an 18650 li-ion cell with a capacity of 2500 mAh and a paraffin based PCM was used. Results from the study indicate that when the li-ion cell is cooled with just the PCM, it does not perform well at high discharge rates whereby the cooling efficiency of the system at a 2C discharge rate was 2.77% lower than the battery without PCM cooling while the cooling efficiency of the li-ion cell at a 1C discharge rate is at 6.17% lower of a battery without PCM cooling. The triangular, rectangular and circular fins were then implemented and the overall maximum temperature of the battery at the end of the 2C discharge rate were 35.9 °C, 35.4 °C and 36.2 °C respectively while the temperature of the li-ion cell with just the PCM alone was 38.5 °C which would indicate the necessity of including the fins.

When comparing the difference in cooling effectiveness between the circular and longitudinal fins, both fin types has its distinct advantages in which the longitudinal fins had better heat dissipation when cooled by air convection while the circular fins had greater heat conduction within the PCM. For the longitudinal fins, the optimal number of fins

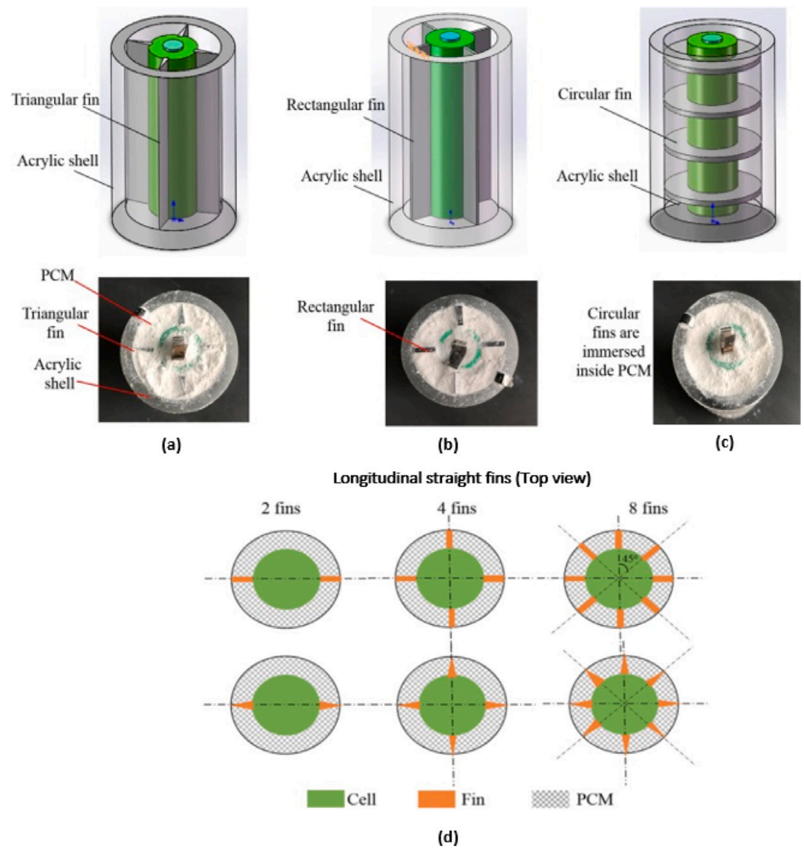


Fig. 24. Investigation on differing fin configuration and the effects of changing the number of fins (a) Triangular fin PCM cooling (b) Rectangular fin PCM cooling (c) Circular fin PCM cooling (d) Altering the number of fins for both triangular and rectangular fins to determine thermal conductivity effectiveness [7].

and its corresponding geometry that has the highest cooling efficiency is a four fin rectangular model in which the maximum temperature of the battery dropped from 36.9 °C to 34.2 °C. In a previous study conducted by Weng et al. [80], it was determined that the bottom segment of a cylindrical li-ion cell cooled purely through PCMs is not able to dissipate heat as effectively. Therefore, it was proposed to have the bottom segment of the PCM cooling system to have cylindrical fins while the top section with longitudinal fins to achieve an optimal thermal balance.

Upon further optimization, it was determined that the most optimal fin structure for PCM cooling for the 18650 li-ion cell are two circular fins at the bottom and 4 rectangular longitudinal fins at the top. To better enhance the thermal conductivity at a pack level design, further optimization of the required fin arrangement should be based on the size of the cylindrical cell and the required charge/discharge current of the battery pack. While the addition of thermally conductive fins does significantly improve the thermal conductivity of the PCM, the addition of such fins will increase the manufacturing cost of the battery pack as additional machining is required to add such fins to the battery pack. The volume required by the fins to effectively improve the thermal conductivity of the PCM would also simultaneously increase the size of the battery pack.

6.2. Thermally conductive coating

A secondary alternative to fin thermal conductivity enhancement is through PCM micro-encapsulation. The process involves encapsulating the solid–liquid PCM with a stable polymer film that is thermally conductive by polymerization through suspension, emulsion, interfacial and other such means [76]. The shell material can be divided into three categories which are organic, inorganic and an organic–inorganic hybrid as displayed in Fig. 25.

Organic shell materials have good sealing properties and structural flexibility, allowing them to perform well at handling the repetitive volume changes during the phase change process of the core PCM material [83]. The most common organic shell materials used are melamine formaldehyde resin, urea formaldehyde resin and acrylic resin [84–86]. Singh et al. [87] investigated the thermal performance of several 3.0Ah Sony 18650 li-ion cylindrical cells which are encapsulated with a layer of n-eicosane, a PCM coated in a urea formaldehyde polymer shell. The cells are modeled under forced convection with different discharge rates and arranged with both a staggered and inline arrangement. Results obtained from the CFD study show that even with a 1 mm encapsulation layer around the cell, there is a significant reduction in battery temperature even at high discharge rates as compared to the same battery without PCM encapsulation. Additionally, each arrangement, discharge rate and inlet velocity have its own optimal encapsulated PCM thickness signifying that the thickness of the encapsulated PCM has to be based on the parameters of the pack itself.

Srivastava et al. [88] conducted a similar study through experimental and numerical means by discharging a 2.6Ah 18650 li-ion battery cell encapsulated with eicosane PCM under different discharge rates and ambient temperatures as displayed in Fig. 26. The same battery is also encapsulated with two different PCM types which are Rubitherm 42 and capric acid. From the investigation, it was determined that the battery encapsulated with eicosane PCM had a lower temperature rise as compared to the battery with RT42 and capric acid as long as the ambient temperature does not exceed the melting temperature of the respective PCMs.

There are several weaknesses though for organic shell materials in which they are combustible, have poor thermal conductivity and have poor mechanical properties which limit the use of organic micro-encapsulated PCM for BTMS applications [89]. Compared to organic

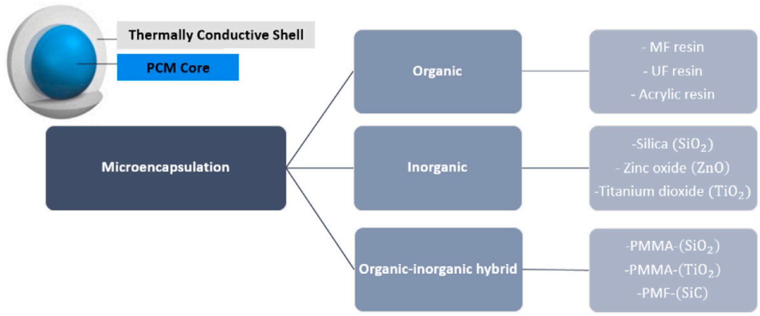
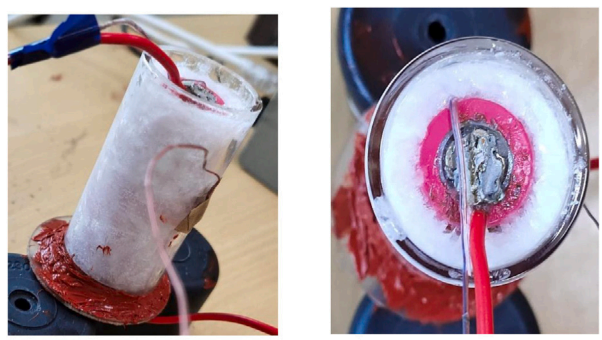


Fig. 25. Different micro-encapsulation for PCM thermal conductivity enhancement [81,82].



(a) (b)

Fig. 26. li-ion Battery assembly encapsulated with Eicosane (a) Isometric view (b) Side view [88].

shells, inorganic shells are better thermal conductors, provide good rigidity and have better mechanical strength [83]. Commonly used inorganic shells are Silica (SiO_2), Zinc Oxide (ZnO), Titanium Dioxide (TiO_2) and Calcium Carbonate (CaO_3) [90–93]. Jiang et al. [93] encapsulated paraffin with a CaO_3 shell. Under optimal conditions with styrene-maleic anhydride as an emulsifier and a pH value of 7, the paraffin and CaO_3 core–shell structure has an encapsulation ratio of 56.6% and leakage rate of 2.88% while significantly improving the thermal conductivity of the paraffin core–shell structure. Fang et al. [94] encapsulated paraffin instead with a SiO_2 shell. The encapsulation ratio was improved at 87.5% with good thermal conductivity enhancement as well. Despite the improvement in thermal conductivity and other mechanical properties, inorganic shell materials have less flexibility than organic shells which would lead to PCM core leakage after several phase change cycles.

Organic–inorganic hybrid shells improve on the weaknesses of purely organic and inorganic shells and provides good mechanical strength, thermal conductivity, chemical stability and shell flexibility [83]. Examples of commonly utilized organic–inorganic hybrid shells are polymethylmethacrylate and polymelamine formaldehyde shells doped with SiO_2 or TiO_2 [95,96]. Wang et al. [97] synthesized micro-capsules which comprises of a n-octadecane cores and a polymelamine formaldehyde and silicon carbide hybrid shells through in-situ polymerization. In comparison without the added inorganic Silicon Carbide shell, the addition of 7% Silicon Carbide greatly improved the heat transfer rate and increased the thermal conductivity of the micro-capsule to 60.34%. Thus, organic–inorganic micro-encapsulation could be considered for PCM thermal conductivity enhancement as it provides sufficient thermal conductivity enhancement while being mechanically stable and with minimal PCM core leakage. It should be noted that the feasibility of PCM micro-encapsulation is hindered by the complex chemical process required to synthesize the encapsulation along with the difficulty in procuring the necessary chemical compounds needed to produce the encapsulation.

6.3. Thermally conductive fillers

The third thermal conductivity enhancement technique for PCMs is through the addition of thermally conductive fillers such as with nano-particles, metallic particles, metallic foam and carbon nanotubes. By mixing in such fillers, the thermal conductivity and efficiency of the PCM can be greatly enhanced and would reduce the flammability of the organic PCM [98–100]. Xiao et al. [101] prepared a paraffin/nickel and paraffin/copper foam composite PCM through vacuum and non-vacuum means and its thermal conductivity is experimentally measured and compared to the thermal conductivity of a pure PCM and a theoretical value. From the results of the experiment, the thermal conductivity of the paraffin/nickel composite is approximately three times that of the pure PCM while the paraffin/copper foam composite is 15 times that of pure paraffin. Notably, the melting temperature of the metal foam composite increases while its freezing temperature decreases which may affect the effectiveness of the composite for BTMS applications. Inversely, the metal foam/PCM composite exhibits lower specific heat capacity values as compared to pure PCMs for both solid and liquid form.

Kumar et al. [102] investigated the effects of mixing graphene particles into a PCM mixture to observe its effects in enhancing the PCM's thermal conductivity. It was determined that the best composition of a graphene-PCM mixture is at 2.0% mass fraction of graphene which increased the thermal conductivity by 66.15%. Increase in graphene mass fraction above a 2.0% would lead to clusters across the PCM leading to lower temperature uniformity. Ling et al. investigated the effects of combining the organic PCM Rubitherm 44HC with expanded graphite (EG) on the thermal conductivity of the composite. EG with mass fractions of 25% and 35% of the total PCM mass were constructed by submerging the EG in the melted liquid PCM at 60%. Several observations were made whereby the thermal conductivity of the PCM/EG composite remains independent of the temperature of the PCM/EG but increases greatly with the phase change temperature. Additionally, while increasing the mass fraction of the EG will increase the thermal

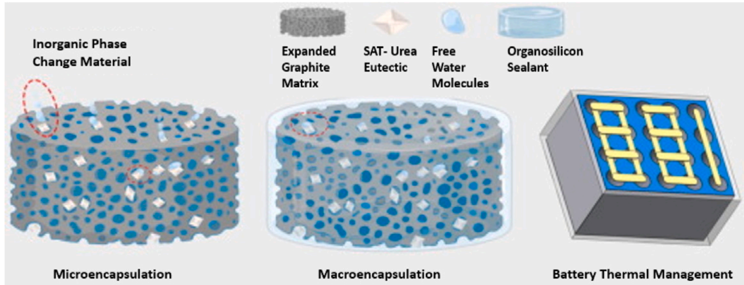


Fig. 27. Multi-scale encapsulation of sodium acetate trihydrate urea PCM to prevent dehydration while improving thermal conductivity [104].

conductivity of the PCM/EG composite the specific heat capacity and latent heat capacity will decrease simultaneously. Thus, the addition of such thermally conductive fillers does increase the thermal conductivity of the PCM by a significant value but would also decrease its specific heat capacity and as such a balance of the required mass fraction of thermal conductivity enhancement fillers are needed. The fillers might also be further aggregated over repeated phase change cycles and as such have to be remixed to improve temperature uniformity of the PCM.

6.4. Inorganic PCM

There are various types of inorganic PCMs which include molten salts, hydrated salts and metals with several advantageous properties for thermal energy storage applications such as having a higher latent heat capacity, non-flammability and they have relatively low cost as compared to organic PCMs. However, the main reason most researchers do not utilize inorganic PCMs is because of its corrosive properties, higher phase change temperatures, similarly poor thermal conductivity, heaviness, lack of stability for repeated phase change cycles due to phase separation, dehydration and sub-cooling [4,28,103]. The main impediment to its adoption for thermal energy storage applications is its dehydration factor which would cause the inorganic PCM to be unstable [104]. Ling et al. [104] attempted to overcome such a disadvantage through a multi-scale encapsulation method of an inorganic PCM, sodium acetate trihydrate urea with the goal of preventing dehydration and improving its thermal conductivity as displayed in Fig. 27.

The compound was prepared by firstly mixing the sodium acetate trihydrate urea with EG with mass fractions between 75 to 82 percentage by weight (wt%). Graphite powder at a mass fraction of 0.5 to 3.0 wt% was added as both a nucleating agent and to reduce the supercooling degree. Finally, the composite is covered in a layer of tinfoil and 5 mm organosilicon sealant to prevent dehydration and improve the phase cycling ability of the salt hydrate. The thermal conductivity of the inorganic PCM composite reached 4.96 $Wm^{-1}K^{-1}$, has sub-cooling temperatures of 1.6 °C and handles well after 100 phase change cycles with a small deviation of phase change temperature of 1.7 °C and phase change enthalpy by 6.9%. When the same inorganic PCM composite was utilized as a BTMS for a battery pack, the maximum battery temperature was controlled to be below 52.3 °C at a 2C discharge rate and a maximum battery cell temperature difference below 4.0 °C for a twenty cell battery pack showcasing the effectiveness of inorganic PCMs for BTMS applications.

Galazutdinova et al. [105] compared the thermal and mechanical properties of two different inorganic PCMs against an organic paraffin wax PCM to determine which PCM is best suited for BTMS applications. The inorganic PCMs utilized were $MgCl_2 \cdot 6H_2O/Mg(NO_3)_2 \cdot 6H_2O$ with a mass fraction of (41.3 wt.%/58.7 wt.%) and $Bischofite/Mg(NO_3)_2 \cdot 6H_2O$ with a mass fraction of (41.3 wt.%/58.7 wt.%) while the organic paraffin wax PCM used has a melting temperature of 55 °C. The three PCMs are abbreviated respectively as $CPCM_{wax}$, $CPCM_{MgCl2}$ and $CPCM_{Bischofite}$. For added thermal conductivity, the three PCMs are mixed with equal amounts of EG. Several parameters were tested between the three PCMS including the heat flow, compressive strength, young's modulus, thermal expansion and thermal conductivity. The two inorganic PCMs exhibited better heat flow, thermal conductivity, compressive strength and lower thermal expansions than the organic paraffin wax PCM. Between the two inorganic PCMs, the $CPCM_{Bischofite}$ performed better in terms of both mechanical and thermal properties but its stability after several phase change cycles was not tested in the current set of works and is not tested for BTMS applications. In an updated version of studies done by Galazutdinova et al. [106], the three PCM composites with EG are machined to be tested for BTMS applications as displayed in Fig. 28.

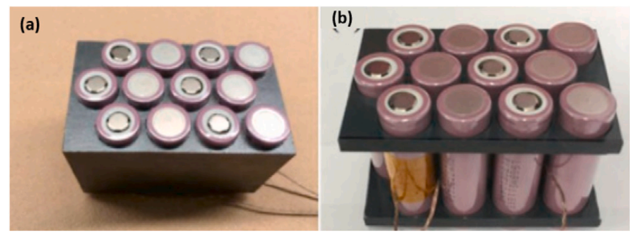


Fig. 28. Test cycle operations for PCM composite for BTMS applications (a) battery pack placed in machined PCM block for electrical cycle test (b) battery pack tested without PCM [106].

Electrical cycling tests are conducted at ambient temperatures with discharge rates of 0.5C, 1.0C, 2.0C and each of the respective discharge rates are repeatedly charged and discharged three times. The maximum battery temperature and maximum temperature difference of the cells in the battery pack are recorded after each cycle and tabulated. For comparison, a battery pack with no PCM cooling undergoing similar discharge rates and cycles has its maximum battery temperature and the maximum temperature differences compared to the three PCM cooled battery packs. From the discharge test results, all three of the composite PCM battery packs had lower battery maximum temperatures and better temperature distributions than the battery pack without PCMs. At 1.0C discharge rates, the no PCM battery pack reached maximum temperatures above 49 °C while all three PCM battery packs had maximum battery temperatures below 40 °C. At 2.0C discharge rates, the no PCM battery pack reached maximum battery temperatures above 65 °C which is above the recommended safety limit while all three PCM battery packs had maximum battery temperatures below 65 °C. The inorganic PCM composites remained chemically stable even after three battery charge and discharge cycles but as highlighted by [104], it is with prolonged phase change cycles that causes chemical instability in the organic PCM. As such, the viability of inorganic PCMs can only be determined with longer phase change cycle data.

Thus, it can be concluded that inorganic PCMs can be utilized for BTMS applications, provided that the dehydration factor is effectively

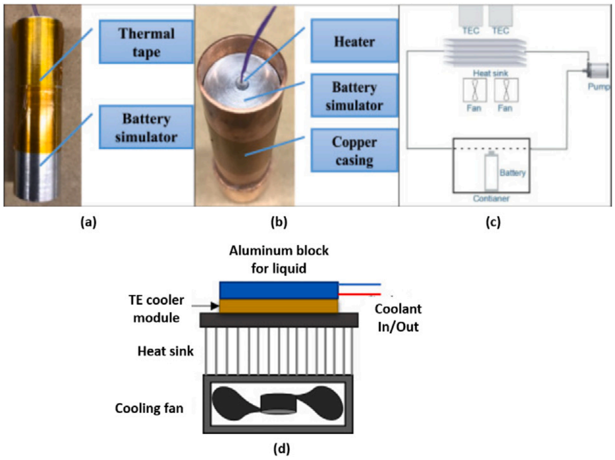


Fig. 29. Hybrid BTMS involving liquid cooling, air cooling and TECs (a) Heat source used as battery simulator (b) Copper casing to improve heat conduction of simulated battery (c) Schematic of hybrid system whereby the simulated battery is submerged in a liquid container which is pumped through a TEC cooling module (d) Condensed diagram of the hybrid cooling system [24].

managed, like with the multi-scale encapsulation technique. Additionally, if the long-term phase-change cycle repeatability of the inorganic PCM is not an issue for the BTMS application incorporated with it, then it should be feasible as well. At present, there are not many alternative techniques to deal with the chemical instability of the inorganic PCM which is the main reason why it is not widely adopted for BTMS applications. Hence, increased development in this area is needed for wider adoption.

7. Thermoelectric thermal management

Thermoelectric power generation and thermoelectric coolers (TECs) are also advantageous as BTMS's for they are relatively silent, stable and have better temperature control features through fine adjusting of the voltage [24]. Generally, thermoelectric devices involves converting temperature differences between a cold segment and the heating segment to electric current and vice versa through the Peltier–Seebeck effect along with the Thompson effect. There is a major draw back for thermoelectric systems for BTMS applications in which such systems have low thermal efficiencies and would require additional energy to operate which would lower the thermal efficiency of the battery pack itself [107]. Most literature works would construct hybrid systems between TECs and other forms of cooling including air, liquid and PCM cooling. Lyu et al. [24] constructed a liquid, air, TEC hybrid system to cool a simulated heat load as displayed in Fig. 29. A cylindrical heat load which was meant to represent a li-ion cell encased in a copper cylinder and suspended in a water storage and is pumped through a TEC cooling system that is further cooled by a cooling fan. A constant 40 V was supplied to the heater module, 12 V was supplied to the TEC device and the heater module is heated for one hour to mimic a li-ion cell undergoing a 1C discharge rate. At the end of the heat load test, the surface temperature of the simulated li-ion cell dropped from 55 °C to 12 °C which was a considerably large temperature drop.

Zhang et al. [108] simulated the effectiveness of coupling with a TEC module to both a U-shape and Z-shape cooling plate on prismatic li-ion cell through CFD. The hot component of the TEC is attached to the surface of the li-ion prismatic cell while the cold component is attached to a flat plate. Inlet flow velocity of the coolant was set at 1.0 m/s, the coolant inlet temperature is set at 25 °C and the battery was modeled to have a heating rate of 100 W. The cooling performance of just the cooling plate was modeled together with the cooling plate and the TEC. From the CFD simulation results obtained, the U-shape cooling plate has better temperature distributions than the Z-shape cooling plate but they both have high temperatures at the center as compared to the outer regions. In comparison, the TEC and cooling plate module had a more uniform temperature distribution throughout the battery pack and the maximum battery temperature values are significantly lowered.

Esfahanian et al. [109] hybridized a TEC cooling system with a direct air cooled system for a hybrid bus battery pack. There are 12 packs each containing 14 smaller li-ion cell prismatic cells, the heat generated by the pack is set at 200 W, the upper tabs of the li-ion cells are attached to the hot side of the TEC and the cold region is attached to heat sinks which is further cooled by cooling fans. The simulated CFD results indicate that the TEC Air Cooled system was able to keep the maximum battery temperature values below the safety limit of 35 °C and maximum temperature difference at 6 °C. Thus, it can be observed that the hybridization of a TEC component with other forms of BTMS cooling would improve its cooling performance in terms of lowering the battery's maximum temperature and the temperature distribution but would increase the system complexity of the BTMS and would draw more power from the battery pack which could potentially lower the overall efficiency of the battery pack.

8. Discussion

From the review study conducted, it can be deduced that each BTMS system has its own set of strengths and weaknesses that allow them to be favorable for different battery pack specifications. Distinctively, each BTMS can be categorized into passive and active energy systems as presented in Tables 1 and 2 respectively. Air cooling through natural ventilation is the cheapest and most simplistic mode of cooling for a battery pack but it does not provide sufficient cooling for most EV applications due to its low heat capacity and heat transfer coefficients [20]. Hence, it is only viable for EVs that have low charging and discharging rate requirements, small sized configurations and in suitable ambient temperature environments. Heat pipes are able to operate passively and with greater cooling efficiencies than air cooled systems but the large volume of space required, the lack of temperature control and the additional cooling required at the condenser section makes it difficult for heat pipes to be incorporated for EV application. To reduce the volume taken by the condenser section, the condenser should be angled to minimize space.

PCM's show favorable traits as a passive BTMS system as they are able to absorb large quantities of heat and maintain optimal temperatures for prolonged periods due to the high latent heat capacity of the PCM during its phase change transition. PCM BTMSs are also more compact in space requirements as an active cooling component is not needed. However, PCMs require a significant amount of time to resolidify after it melts, there is the risk of the PCM leaking during its liquid state and the large latent heat capacity is only accessible at narrow temperature ranges which prevents the PCM from responding to rapid temperature rises and drops across the battery pack. For organic PCMs, there is also the risk of combustibility in the event of a thermal runaway scenario while inorganic PCMs are chemically unstable after several phase change cycles, have higher melting temperatures and are heavier than organic PCMs. With such considerations in mind, an organic PCM based BTMS can be incorporated into an EV battery pack that has relatively stable thermal conditions and with sufficient flame retardant measures taken on the PCM used [113]. To improve the quality of PCM based BTMS, the container of the PCM has to enhance the thermal conductivity of the PCM, prevent it from leaking and ensure the homogeneity of the PCM over several charge cycles. Hence a PCM BTMS based on thermally conductive coating or a finned container would be the ideal container type.

EVs designed for long distance travel and fast charging require larger battery packs which would produce much higher thermal loads. As such, it is necessary to implement an active cooling based system to dissipate the large quantities of heat generated and accurately control

Table 1
Strengths and weaknesses of passive BTMS systems.

BTMS	Mode of cooling	Strengths	Weakness
Air cooling	Natural ventilation [21,25]	i. Low energy requirements ii. Light-weight iii. Simplistic design iv. Ease of maintenance v. Low operational cost vi. Direct cooling medium contact	i. Insufficient cooling capacity ii. Low cooling efficiency iii. Unbalanced thermal distribution
Liquid cooling	Heat pipe [8,110]	i. High specific heat capacity ii. High thermal efficiency iii. Large cooling surface area	i. Occupies large volume ii. Complex structure iii. Costly iv. Leakage problem v. Condenser section has to be cooled
PCM	Organic PCM [92,111]	i. Low cost ii. Chemically stable and reliable iii. Uniformed temperature distribution iv. High latent heat capacity v. Able to operate passively	i. Low thermal conductivity (Has to be enhanced) ii. Leakage problem iii. Narrow melting temperature range iv. Combustible
	Inorganic PCM [104,111]	i. Low cost ii. Uniformed temperature distribution iii. High latent heat capacity iv. Able to operate passively v. Non-combustible	i. Low thermal conductivity (Has to be enhanced) ii. Leakage problem iii. Narrow melting temperature range iv. High melting temperature v. Chemically unstable vi. Corrosive vii. Heavy

Table 2
Strengths and weaknesses of active energy BTMS systems.

BTMS	Mode of cooling	Strengths	Weakness
Air Cooling	Forced convection (Fan Cooling) [112]	i. Direct cooling medium ii. Light-weight iii. Simplistic design iv. Ease of maintenance	i. Low specific heat ii. Requires additional fan iii. Unbalanced thermal distribution iv. Low cooling efficiency
Liquid Cooling (Indirect)	Cooling plate [8]	i. High specific heat capacity ii. High thermal efficiency iii. Large cooling surface area	i. Costly ii. Risk of leakage iii. Complicated machining required iv. Not suitable for cylindrical cells v. Requires additional pump vi. Short operational lifetime
	Thermally conductive Tubing [8]	i. High specific heat capacity ii. High thermal efficiency iii. Large cooling surface area iv. Flexible	i. Risk of tubing leakage ii. Short operational lifetime iii. Costly iv. Requires additional pump
Liquid cooling (Direct)	Immersion cooling [68]	i. High specific heat capacity ii. High thermal efficiency iii. Occupies least volume iv. Large cooling area	i. Risk of leakage ii. Costly iii. Heavy iv. Complex structure v. Requires additional pump
Thermoelectric	Thermoelectric cooler [24,25]	i. Low maintenance cost ii. Non combustible iii. Structurally stable iv. No risk of leakage v. Static component vi. Accurate temperature control	i. Low thermal efficiency ii. Additional power requirement

the cooling energy needed to maximize the efficiency of the cooling system. Air cooling through forced convection achieves such cooling requirements as the air flow velocity can be optimized to dissipate the heat produced by the battery pack at varying thermal loads. Furthermore, by regulating the inlet and outlet valves such as with the J-Type cooling channel configuration, the airflow can be channeled to further improve the cooling performance of the air cooled BTMS. There are several weaknesses of a fan-cooled air BTMS though which include lower cooling uniformity due to the air swirled within the pack and low cooling efficiencies due to the low heat transfer coefficient and specific heat capacity of air. Such weaknesses can be compensated for through the addition of thermal conductivity enhancers such as with porous aluminum foam and the installation of heat sinks across the battery pack. Nevertheless, the predominant BTMS used for most EVs are liquid cooled BTMS as liquids often have higher heat transfer coefficients and specific heat capacities than air [20,114].

With prismatic and pouch cells, the utilization of cooling plates allows a greater area of the battery pack to be cooled. Notably, the weight of the aluminum or copper cooling plate would dramatically increase the weight of the EV due to the large surface area of the battery pack that has to be cooled. Furthermore, the regions closest to the outlet of the cooling plate would offer less cooling as the liquid heats up after being passed through a heated battery pack. The only way to alleviate this weakness in cooling uniformity is to increase the number of parallel lines across the cooling plate. Alternatively, thermally conductive tubing are flexible and lightweight which allows it to cool a wider range of battery geometry types while providing sufficient cooling performances. Such tubing's can be designed to be wide enough to cover a substantial area of the battery pack or narrow enough for multiple smaller tubes to be passed through the gaps between each li-ion cell. Similar to the cooling plate, the region cooled closest to the outlet would also have the worst cooling performance as the liquid coolant would absorb most of the battery pack's heat at that point. Hence, a larger number of parallel tubes are preferred over a serpentine configuration. It should be noted that the tubing has a greater possibility of leakage as compared to a cooling plate as it is not as structurally tough as compared to the compact and dense design of a cooling plate. As such, the tubing has to be regularly inspected and replaced if needed to prevent leakage onto the battery pack.

Immersion cooling offers the greatest cooling efficiency and best cooling uniformity as compared to the other liquid cooling strategies. By soaking the battery pack in dielectric fluid, the cooling surface area available is maximized and coupled with the high specific heat capacity of the dielectric fluid the battery pack is able to achieve high charge and discharge rates. The risk of thermal runaway is also greatly reduced due to the non-flammability of the dielectric fluid [71]. Most dielectric fluids are costly though and a substantial volume of it is required to cool the entire battery pack. Hence, immersion cooling is better suited towards high performance EVs that produce high thermal loads. TEC's are able to accurately control the amount of heat dissipated from a battery pack but it does not provide sufficient cooling efficiencies to cool a battery pack on its own. Hence, it is usually coupled with other cooling systems such as with an air or other liquid cooled system as a means of accurately controlling the amount of heat to be dissipated.

By examining the strengths and weaknesses across each type of BTMS type, it becomes apparent that certain BTMS variants are better suited for specific types of EV types. Many novel findings were made for each BTMS type. For the results obtained in the air cooling section, the main findings from the studies include the effectiveness of a hexagonal li-ion cell array arrangements and optimized inlet and outlet configurations to enhance cooling performance [33,34,99]. However, these improvements are countered by challenges such as increased pack volume, potential busbar configuration impacts, and concerns about heightened battery pack dimensions and reduced effectiveness. Streamlining cooling channels, notably through secondary outlets and spoilers [40,42], showed promise in cooling performance and power consumption reduction but increases ducting complexity. Additionally, the use of thermal conductivity enhancers [43,44], while improving cooling uniformity and structural strength, raised concerns about an augmented overall weight of the battery pack. The current EV industry favors compact BTMS types that can accommodate both small and large power loads across the battery pack while being as compact as possible. As such, thermal conductivity enhancers such as with the pin fin heat sinks and increasing the inlet points might be of benefit in enhancing air based BTMS for industry use.

The findings from liquid BTMS studies also reveal several notable enhancement techniques. Optimizing cooling plate channels by increasing width proves more effective than adding channels, providing a large surface area and efficient cooling for pouch or prismatic cells [57]. The use of thermally conductive tubing, particularly with added aluminum housing, ensures improved thermal distribution conforming to cell geometry, although risks of leakage and increased weight are associated [58]. Angled condenser sections in heat pipe arrangements offer passive cooling benefits but require consideration of protruding sections and limitations in high discharge rate cooling [64]. Direct cooling methods, such as two-phase immersion cooling, showcases good convective heat transfer but come with challenges like gradual coolant loss and increased system complexity, while single-phase immersion cooling provides cost-effective and maintenance-friendly alternatives but increases weight due to larger coolant volumes [68]. Present liquid BTMS typically utilize cooling plates for pouch cells and flexible cooling tubes for cylindrical cells; therefore, optimizing cooling channels based on depth would be beneficial, and the addition of aluminum housing would improve the thermal conductivity of the overall pack.

The examination of PCM-based battery BTMS also reveals several notable findings. The addition of circular fins at the bottom and longitudinal fins at the top in PCM fins proves to be an optimal strategy for cooling, enhancing thermal conductivity and structural strength, albeit with potential drawbacks such as the risk of PCM leakage during the liquid state, increased manufacturing cost, and the potential enlargement of the battery pack [7]. Employing a thermally conductive coating with shell thickness based on the heat generation of the battery pack emerges as an effective approach, preventing PCM leakage and offering adaptability for various Li-ion cell geometries, although it involves a complex chemical coating process [81,82]. The use of thermally conductive fillers, specifically paraffin/nickel composites, demonstrates superior performance without requiring a complex chemical process, yet it contributes to an overall increase in the battery's weight [101]. Additionally, the incorporation of graphene at 2.0% mass fraction in the PCM mixture provides adequate thermal conductivity, but higher concentration levels lead to clustering, requiring periodic mixing for even filler distribution [102].

Inorganic PCMs, often overlooked due to corrosive properties and phase change challenges, are reevaluated in this study. The research introduces a multi-scale encapsulation method to mitigate dehydration issues, showcasing the potential of inorganic PCMs for BTMS applications [105]. Comparative studies with organic PCMs and analysis of thermal and mechanical properties demonstrate the viability of inorganic PCMs, provided long-term phase change cycle stability can be addressed. The current suitability of PCM-based BTMS for EV usage is limited due to its ability to cool only a narrow temperature range of the EV and the high risk of leakage. Its likelihood for adoption will only be feasible if a PCM with a wider melting temperature range is made available.

The primary limitation of the study is that experimental cooling systems, such as those utilizing PCM or thermoelectric BTMS, do not take into consideration the overall EV architecture. The conducted studies are confined in scope to analyzing improvements solely on the battery pack without accounting for other factors, such as potential increases in weight or volume for the EV. Further investigation into how these BTMS enhancement techniques may impact the EV would be beneficial.

9. Conclusion

This study reviews the latest developments in BTMS technologies as well as explores the strengths and weaknesses of each BTMS type available. Essentially there are four types of BTMS systems available in the EV industry which include air cooled, liquid cooled, PCMs and thermo-electric based BTMS. There are also hybrid systems which combine the components of two or more BTMS types such as with a combination of air and liquid cooled systems to improve upon the cooling performance of a singular BTMS type.

Air cooled systems have low energy requirements, require the least amount of maintenance and are cheap to install but they do not provide sufficient cooling efficiencies for battery packs with high thermal loads. Hence it is better suited for EVs that are designed for short distance travel and have low thermal load requirements. Liquid cooled BTMS have better heat transfer coefficients, higher specific heat capacities and more uniformed cooling distributions than air but are costlier, heavier, and require much more maintenance. EV's that have larger battery packs, are catered for long-distanced travel and produce high thermal loads are best suited for this type of BTMS. PCM BTMS types are able to absorb large quantities of heat during its phase change cycle and are able to operate passively. However, the thermal conductivity of the system is low and the high latent heat capacity is only available at a narrow temperature range. The thermal conductivity of PCMs can be improved through a variety of methods including the encapsulation of the PCM in a thermally conductive material, the addition of carbon-based or metallic fillers and with the insertion of heat sinks. It could be applied for EVs that generate constant thermal load values and when the ambient temperature surrounding the EV is relatively stable. Thermo-electric cooling offers greater temperature control but has insufficient cooling efficiencies as a standalone system to be used as a BTMS. Hence it should be coupled with other BTMS types to accurately control the temperature of such battery packs. Hybrid BTMS are able to combine the strengths of two or more BTMS types but would further increase the complexity and cost of the BTMS. Thus, the hybrid BTMS combination chosen should balance out the advantages and disadvantages of each system before being implemented.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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