World Journal of Advanced Engineering Technology and Sciences
eISSN: 2582-8266
Cross Ref DOI: 10.30574/wjaets
Journal homepage: https://wjaets.com/

(Review Article)

Check for updates

Review of battery thermal management for electric vehicles in Indian regions

Madaka Ramu, SR Shravan Kumar and G Amba Prasad Rao *

Department of Mechanical Engineering, NIT Warangal-506004, Telangana, India.

World Journal of Advanced Engineering Technology and Sciences, 2022, 07(02), 113–129

Publication history: Received on 18 October 2022; revised on 29 November 2022; accepted on 01 December 2022

Article DOI: https://doi.org/10.30574/wjaets.2022.7.2.0138

Abstract

Internal combustion engines run automobiles have become indispensable due to their versatility in accommodating both liquid and gaseous fuels derived from petroleum reserves. Extensive use of these stored fuels main sources of ground level greenhouse gases due to their in complete combustion due to many reasons. Researchers and manufacturing units of automobiles have been trying their best to meet as per strict emission norms while incorporating after treatment devices and alternative fuels. However, due to non-compliance of emission norms, many nations are seriously shifting towards electric mobility. Battery, electric motor and fuel cell units have become the target for meeting energy demand for electric vehicles. Among various types of batteries, lithium-ion batteries, because of its high specific energy and light weight, have become major source for almost all variants of electric vehicles. But lithium-ion batteries are very sensitive to change in temperature. Due to its usage being exposed to different operating conditions and ambient, thermal runaway has become predominant issue. Thermal runway has become major cause of hazardous accidents. Proper thermal management is essential to maintain lithium ion battery in the range of 15 °C to 40 °C with temperature difference among cells inside the battery pack less than 5 °C, for majority of regions of Indian terrain. Between internal and external thermal management systems, external system is more preferable. With air cooling unit has emerged as effective. The present paper reviews various external battery thermal management systems including active, passive, air, liquid, phase change material and heat pipe-based systems.

Keywords: Battery Electric Vehicle; Thermal Management; Internal; External; PCM; Heat Pipe

1. Introduction

With the advent of petroleum fuel driven vehicles, about more than a one and half century ago, the lifestyle of human beings has tremendously improved in respect of personal transport as well as goods transport. In addition, industrial civilization further added to the growth of other industries that support the automotive industry. With a large-scale increase in the automotive population, the burden on fossil fuels has not only increased but also the nation's exchequer is being overspent. Moreover, with increase in fossil fuel exploration, the associated combustion generated emissions are increasing heavily with the release of greenhouse gases. The increase in use of fossil fuels inadvertently raising the doubts of its availability for future generations matching with demand requirements. All these issues undoubtedly have been deliberated and made room for the use of feasible alternative fuels such as alcohols, CNG, H_2 ,biodiesel etc... However, these fuels have their own merits and limitations. Since the ground level pollution emanating from tails pipes of automobiles is becoming serious and the efforts are being shifted towards electrification of automobiles. However, total use of pure electric vehicles is still being debated, hybrids could be seen as an immediate solution in the run for electric mobility.

In majority of electric vehicles, batteries are major source of power and many types of batteries have been explored. Among the various types, lithium-ion batteries have become indispensable relative to other batteries owing to its high

* Corresponding author: G Amba Prasad Rao
Department of Mechanical Engineering, NIT Warangal-506004, Telangana, India.

specific energy and power, higher energy and power density, lower self-discharge rates, long cycle life, out of all the batteries lithium-ion batteries became most promising power source for electric and hybrid electric vehicles [1,2].

But irrespective of these many attractive properties, lithium-ion battery powered electric vehicles are not widely used by the consumers because of the obstacles like limited calendar life, high cost, and safety concerns [3]. Therefore, lot of research is going on lithium-ion batteries and the researchers are indicating that the lithium-ion batteries will be improved in terms of safety, cost, power and energy capabilities in the upcoming years. However, performance degradation and thermal safety are still the major problems for electric vehicles powered by the lithium-ion batteries. The safety, cycle life, and the capacity mainly depend on the battery temperature. But lithium-ion batteries are very sensitive to change in temperature. The lithium-ion battery performance declines very rapidly for the abnormal temperature range irrespective of the material of the cell [4].

1.1. Effect of Temperature on the performance of battery:

It is observed the in the performance evaluation, the operating/surrounding temperature of battery plays a vital role. When the temperature of battery is too low the rate of chemical reactions will be reduced in the cell which results in decrease in the production of electric power. Therefore, the battery's performance will be significantly reduced with decrease in temperature. With the decrease in temperature, contraction of the electrode materials takes place, which results in slowing down of ion movements. If the temperature keeps on decreasing, then the electrodes will stop accommodating current flow which results in decrease in power output and capacity loss due to lithium plating of the anode [5].

Battery cell temperature	Cause	Leads to	Effect
High	Electrolyte decomposition	Irreversible lithium loss	Capacity fade
	Continuous side reactions at low rate	Impedance Rise	Power fade
	Decrease of accessible anode surface for Li-ion intercalation		
	Decomposition of binder	Loss of mechanical stability	Capacity fade
25 °C – 40 °C	Maximum cycle life		
15 °C – 24 °C	Superior energy Storage capacity		
Low	Lithium plating	Irreversible loss of lithium	Capacity/ power fade
	Electrolyte decomposition	Electrolyte loss	

Figure 1 Effects of operating temperature of battery [6]

It was observed that in low operating temperatures like $-40^{0}C$, lithium-ion battery cells of 18650 type can supply only 1.25% of the power capacity and 1.5% of the energy capacity available at $20^{0}C$. Similarly, it was observed that the 2012 Nissan LEAF's driving range was dropped from 138 miles in ideal conditions to 63 miles at $-10^{0}C$ [6]. Low operating temperatures mostly occurs in high latitude locations such as Canada, Russia and Greenland Island. In these locations, during winter season the atmospheric temperatures will be less than $0^{0}C$. If we use lithium-ion batteries in outer space like mars, the temperatures might be as low as $-120^{0}C$ which makes it difficult to use lithium-ion batteries in astrovehicles during space exploration [7].

Unlike lower temperatures of battery which mainly depends on temperature of environment, most of the times the high temperatures of batteries occur because of the heat generated inside the battery during operations with fast charging and fast discharging [7]. When the temperature of battery is too high [> $40^{0}C$], side reactions inside the batteries will be intensified which will result in capacity loss and life aging and when the temperature is greater than $70^{0}C$ thermal runaway may take place, which is a serious issue because of which fire or explosion accidents of electric vehicles are frequently taking place resulting in a lot of attention to electric vehicles safety [8]. Some of the accidents because of thermal runaway that took place around the world have been reported in literature [5]. Amine et.al investigated the storage and cycling characteristics of lithium-ion cells at high temperature. After 100 cycles, they found a 70% reduction of capacity at 55^0C temperature when compared to 40% reduction at 37^0C temperature [9].The causes and effects with operating temperature of battery have been observed by many researches, and few of them are shown in Fig.1.

The research shows that the temperature of lithium-ion battery has to be maintained in the range of 15°C to 40°C to utilize its maximum effectiveness. Any temperatures outside this range will result in significant loss of capacity [10]. Motloch et al. [11] stated that in the range of 30 to 40 °C for every degree's rise in temperature, there is almost two months decrease in calendar life of the battery. The non-uniform temperature distribution among battery cells also reduces strength of few cells. During charging of the battery, these cells will be overcharged, and these cells may fail. Xuning Feng et al. [12] investigated the mechanisms of the status change of cell variations caused by temperature non-uniformity among cells in a battery pack. It was observed that when the temperature difference among cells inside the battery pack is more than 5 °C, the power capacity of the battery is reduced by 2 % .

Therefore, in order to ensure safety of the electric vehicles which are powered by lithium-ion batteries, the temperature of the lithium-ion batteries should be maintained in the range of 15 °C to 40 °C with temperature difference among cells inside the battery pack less than 5° C. To maintain this an effective BTMS need to be installed in the electric vehicle so that it can decrease the temperature by taking away the heat generated during discharge and also can preheat the battery whenever needed.

2. Battery thermal management system [BTMS]

BTMS can be called as the brain of a battery pack. Several battery cells are arranged in a battery pack in series, parallel or combination both series and parallel depending upon the requirement [13]. To maintain the temperature of the lithium-ion battery pack in the range of 15 °C to 40 °C with temperature difference among cells less than 5° C, a proper BTMS need to designed. A proper BTMS should have 1) It should absorb or release heat whenever needed to maintain the temperature of the batteries in the desired range. 2) Maintains small temperature variations within cell module and various modules inside the battery pack. 3) It should be reliable, compact, lightweight, easily packaged and low cost. 4) Ventilation should be provided if battery generates any hazardous gases [14]. BTMS is of two types. They are i] Internal BTMS which modifies interior parts of the battery like cathode, anode and electrode and ii] External BTMS which dissipates heat from the cells. Fig. 2 shows the classification of BTMS in detail.

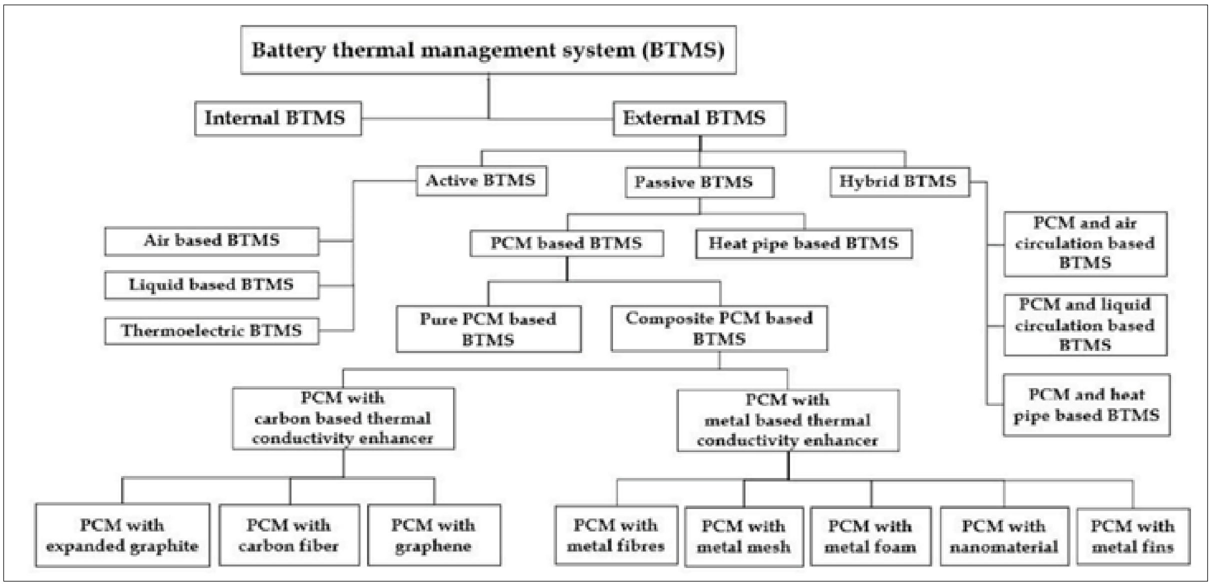

Figure 2 Classification BTMS [10]

3. Internal BTMS

In internal BTMS, interior modifications like selecting the material of the electrodes, thickness of the electrodes as well as their properties like thermal conductivity, thermal diffusivity etc. can be done [15]. Chan et al. [16] used silicon as anode material in lithium-ion battery because of its advantages like high charge capacity and low discharge potential. Sheu et al. [17] studied the effect of particle size of lithium cobalt oxide in the Li/$LiCoO_2$ rechargeable battery system. It was observed that the particle size is influencing the cyclic stability battery.

Wenquan Lu et al. [18] reported that to utilize 70% of the total energy of lithium-ion battery thickness of the cathode should be greater than or equal to 130mm. Wenquan Lu et al. [19] also calculated and plotted the variation of battery volume and weight with respect to thickness. For $LiFePO_4$ cathode Jinli Yang et al. [20] compared three carbon supporting structures like acetylene black, carbon nanotubes, and graphene. They have observed that both electrochemical performance and particle-size of $LiFePO_4$ depends on the carbon supporter and the results indicated that graphene can be a good carbon supporter for $LiFePO_4$.

4. External BTMS

In external BTMS the battery cells can be cooled by using medium like water, air etc. External BTMS can be classified into two types active and passive BTMS based on the use of extra power sources. Active BTMS consumes extra power to run fans or pumps. The air and liquid based BTMS comes under active BTMS. In passive BTMS, particular structures will be attached to the batteries for enhancing the heat transfer from the battery to the outer space. Phase change materials [PCM] based BTMS, and heat pipe based BTMS comes under passive BTMS [21].

Compactness, low cost, low maintenance, vehicle compatibility and reliability are the desirable features of an external BTMS [22].

4.1. Air based BTMS

Air cooling BTMS can be classified based on different air sources, like air cooling BTMS that uses only external air may be natural convection or forced convection as shown in Fig. 3 and the other that uses preconditioned cabin air as shown in Fig. 4. There is another BTMS considering different cooling requirements for battery pack and cabin. To cool battery it uses second evaporator as shown in Fig.5. These three air cooling BTMS are already implemented in most of the commercial vehicles [23].

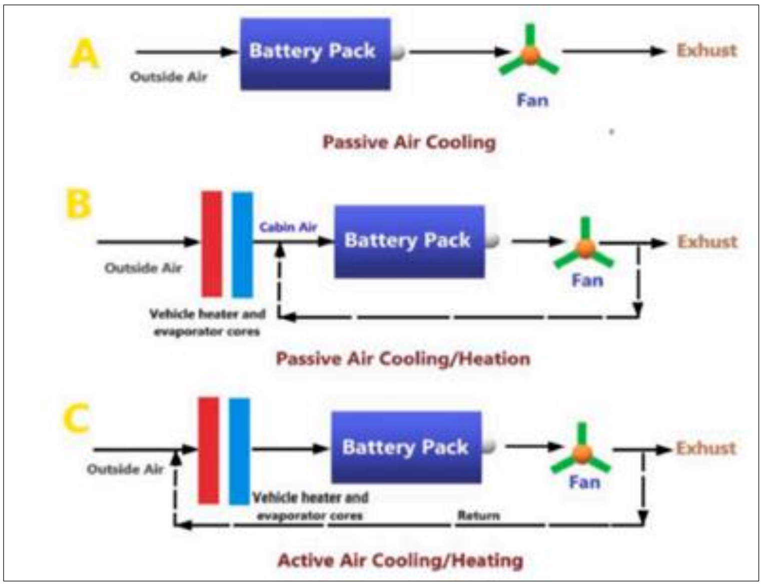

Figure 3 Active and Passive air cooling [24]

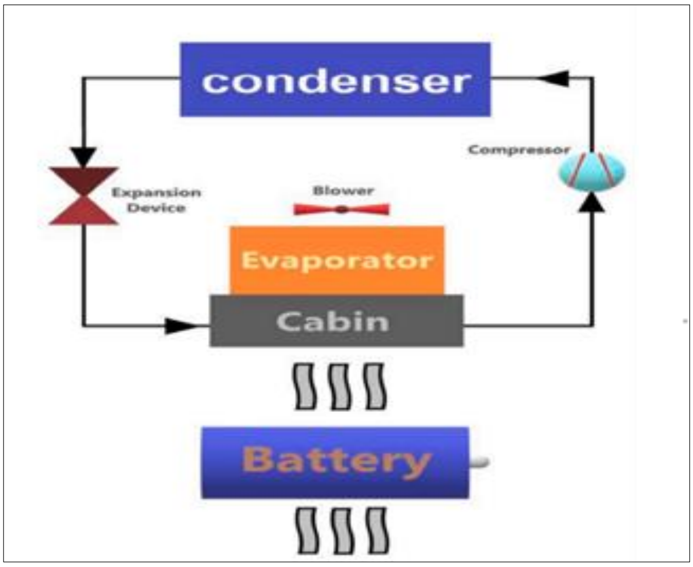

Figure 4 Cabin air cooling [25]

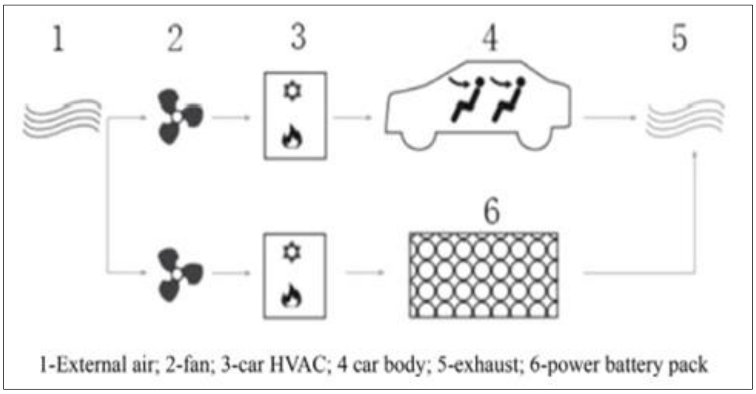

Figure 5 Air based BTMS with an independent "HVAC module" for battery [23]

Air cooling BTMS is the one of the most preferred methods in electric vehicles

because of the many advantages like low cost, simple in design, light in weight, ease of maintenance, ease of replacement of single cell and long life. Hybrid electric vehicles like Honda Insight and Toyota Prius have also used air cooling BTMS. In both the vehicles the battery pack was cooled by using the conditioned air taken from the cabinet and the heat is rejected by the air to the environmentt [26].

Researchers on air cooling in recent years are mainly focusing two things. One is to reduce the batteries maximum temperature and the other is to reduce energy consumption. Many researchers have focused on the effects of different design parameters on the performance of BTMS like the influence of airflow pattern, type of cell arrangement, airflow temperature, airflow rate, and inlet and outlet position [27].

Both natural convection [passive] and forced convection [active] can be used for battery cooling. Since the convective heat transfer coefficient of natural convection is very low, battery cooling by natural convection is effective only for batteries with lower energy density [28].

Kuahai Yu et al. [29] studied the effects of mass flow rate of air on the battery performance. The results shows that by increasing the mass flow rate from 0.2 m3 /min to 1.2 m3 /min the maximum temperature of the battery was decreased from 42^0C to 36^0C . They have also developed a system with airflow in two directions and they have observed the better cooling performance for the cells which are placed in the middle of the battery pack. Xu et al. [30] studied different layouts of battery and observed that by arranging the batteries in horizontal manner rather than longitudinal manner decreases the airflow path, thereby enhances the dissipation of heat by the battery pack. Jiwen Cen et al. [31] studied the cabin air cooling BTMS, and observed that the maximum temperature difference among cells in the battery module is around 2 ∘ C. For effective battery thermal management, they have also used PID control.

Jinhong Xie et al. [32] done the structural optimization of air flow channels and observed that the air flow channels layout impacts a lot on the maximum temperature of the batteries and the temperature difference among cells inside the battery pack. By using orthogonal test method and single factor analysis he optimized the air flow channel width, air inlet and outlet angle. After optimization they observed that maximum temperature is decreased by 12.82% and the temperature difference is decreased by 29.72% .Liwu Fan et al. [33] obtained the tradeoff between the cell spacing and air mass flow rate. It was observed that by decreasing the spacing between the cells we can decrease the temperature and by increasing mass flow rate of air we can improve the temperature uniformity, because convective heat transfer coefficient is increasing with increase in air's mass flow rate.

An air cooled battery module was optimized by Furen Zhang et al. [34], using spoiler. The effect of the position and number of spoilers was investigated. It was concluded that the thermal performance of BTMS is significantly affected by change in the position and number of spoilers. A reduction of 3.4^0C in maximum temperature and 5.9^0C in the temperature difference was observed. Ahmad [35] experimentally studied air based BTMS with series and parallel flows. He observed that there was less temperature unevenness when parallel flow was used.

Jingzhi Xun et al. [36] observed that the cooling effect can be improved by increasing the channel diameter, but it will result in more uneven temperature distribution.

4.2. Liquid based BTMS

The liquid based BTMS has been widely applied in the electric vehicles such as by Tesla and General Motors [37,38]. In liquid based BTMS, the heat is carried away by the conduction and convection from the battery cells to the coolant via many cooling channels. Since water and Ethylene glycol solution have wide operation temperature range from – 40 ∘ C to 105 ∘ C they are the most commonly used coolants. The liquid based BTMS has both high heat transfer rate and efficiency compared to other systems due to high thermal conductivity of the liquid coolants. Since liquids have high specific heat, the mass flow rate required for the liquid based BTMS is much lower than the other BTMS to remove same amount of heat. It means liquid based BTMS consume much less energy than air based BTMS since we use pumps. Besides compared to same power electric air fans, the noise level of electric water pumps is low [39,41]. Liquid based BTMS can be divided into direct contact and indirect contact modes based on whether the battery surface is in direct contact with the liquid coolant [40]. Classification of liquid based BTMS is shown in Fig. [6].

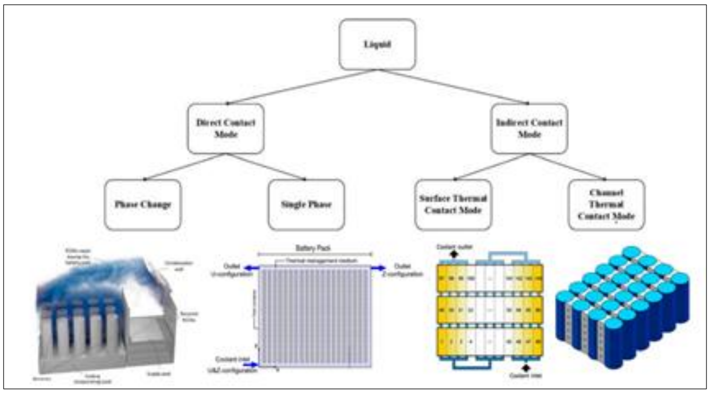

Figure 6 Liquid based BTMS classification [45]

4.2.1. Direct contact liquid based BTMS

In direct contact liquid based BTMS to remove heat from the batteries generally dielectric heat transfer fluids will be used because of the advantages like higher cooling rate and greater compactness compared to indirect contact liquid based BTMS. The heat transfer fluid should be a dielectric [such as silicone based or mineral oils] because it avoids any short circuit. In direct contact liquid based BTMS battery will be directly immersed in the liquid. Therefore, direct contact liquid based BTMS have high heat transfer efficiency. Even though this direct contact liquid based BTMS is not so practical still this is used in extreme situations like high power batteries and high charge rate [42,43,]. The direct liquid based BTMS is divided into two types. The phase change and single phase. Phase change liquid based BTMS is also called as boiling cooling. If the heat transfer fluid's boiling point is less than the maximum temperature of battery, the cooling process will take place by the phase change process. Single phase liquid based BTMS is similar to forced air based BTMS. In single phase liquid based BTMS flow channel design is very much important to enhance the heat transfer [44]. Maan Al-Zareer et al. [45] proposed a phase change liquid based BTMS in which the batteries are partially submerged into the liquid ammonia and by absorbing the heat generated by the battery, the liquid ammonia cools the battery and evaporates and then the ammonia vapor cools the remaining part of the battery which is not covered by the liquid ammonia. Maan Al Zareer et al. [46] also proposed a similar phase change liquid based BTMS in which liquid propane is used as heat transfer fluid. Jiahao Liu et al. [47] designed an oil immersed BTMS to study the feasibility of the stationary transformer oil fluid on battery thermal management. The results have shown that at 2C discharge rate, maximum temperature of the battery which is immersed in the transformer oil was found to be 37.35^0C and the maximum temperature inside the battery was found to be 2.64^0C which is very much lower than that which is exposed to the open air. Zhechen Guo et al. [48] designed a lightweight direct contact liquid based BTMS with multichannel and observed that by using this design, at 3C discharge rate the maximum temperature of the battery can be controlled below 36^0C and the temperature difference inside the battery can be limited to 0.65^0C .

4.2.2. Indirect Contact liquid based BTMS

Even though the direct contact liquid based BTMS has good thermal performance most of the electric vehicles don't prefer this because it is not that much practical [51]. Implementation of indirect contact liquid based BTMS is easy and in addition low viscosity fuels [unlike direct contact liquid based BTMS] can be used which reduces the pumping power required in indirect contact BTMS [49,52]. Liquid based BTMS generally use indirect type to avoid the electrical short circuit and chemical erosion by separating battery from the coolant by using auxiliary devices like cold plate, discrete tubes [38]. Cold plates are like heat exchangers which consisting of many number of channels through which coolant flows which absorbs heat from the batteries which are in contact with the cold plate as shown in Fig.7. Mini-channels are used in cold plates because they offer less thermal resistance and more heat transfer area per unit volume. Channel geometries of cold plates can be circular, square, rectangular or polygonal with hydraulic diameters in the range of 1 to 6mm. Mini channel cold plates are compact, robust, lightweight. They are easy to integrate particularly with prismatic batteries and offers high heat transfer [50,53].

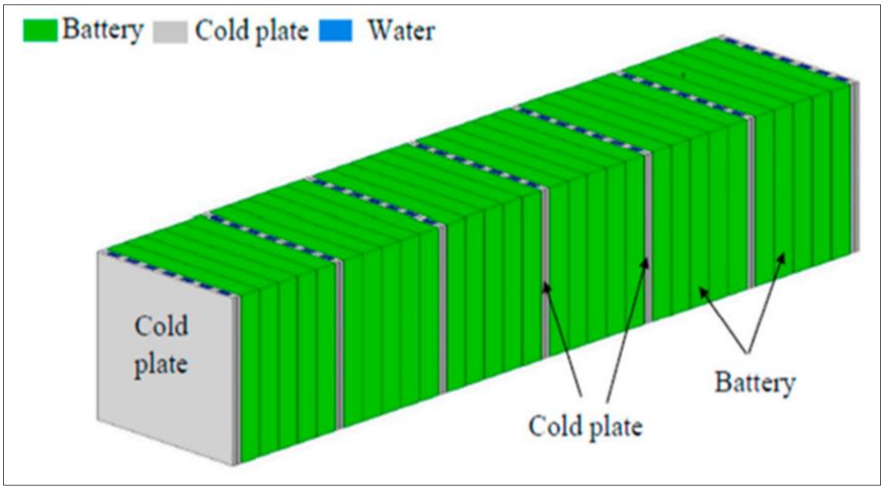

Figure 7 Schematic of the battery pack with cold plates [53]

Amalesh et al. [53] proposed seven different new designs of mini-channel cold plates and studied the role of profile of the channel on the performance of mini-channel cold plates. The results indicate that the profile of the channel strongly influences the hydraulic and thermal performance of cold plates. Shuguang Zuo et al. [54] studied the effect of vibration on the performance of mini-channel cold plate because the battery pack will be subjected to vibrations during the operation of electric vehicle. They have varied amplitude, frequency of vibration and mass flow rate and observed that the performance of cold plate can be improved by vibration.Tao Deng et al. [55] studied a mini channel cold plate with serpentine channel by varying layout of the channel, number of cooling channels, and coolant inlet temperature. It was observed that, the channels in the direction of length achieving better performance than that in the width direction. They have also observed that the coolant inlet temperature has small influence on pressure drop and standard deviation of temperature. Lei Sheng et al. [56] designed a serpentine channel cold plate with two inlets and two outlets. They have studied the effects of flow rates, flow directions, and width the channel. It was observed that the flow directions, location of inlet and outlet of coolant have lot of impact on the power consumption and temperature distribution of cell. They have also observed that increasing mass flow rate of the coolant decreases the maximum temperature rise of the battery, but it has very little effect on the temperature distribution of battery. Their results shows that width of the channels has large impact on power consumption and temperature uniformity, but it has little impact on maximum temperature rise of battery.

Yutao Huo et al. [57] studied the effects of mass flow rate, channels number, flow direction and ambient temperature on the performance of the mini channel cold plate. They have observed that by increasing mass flow rate and channels number, the batteries maximum temperature can be decreased. They have also observed that after optimal mass flow rate the performance of cooling plate is not increasing much.

Huaqiang Liu et al. [58] investigated different coolants such as water, engine oil, ethylene glycol and their corresponding nanofluids on the performance of mini-channel cold plate. Results indicate that among the three base fluids water has shown better performance than other two because of high thermal conductivity and after adding nano-particles the performance of three base fluids is improved in such a way that the improvement is more in the fluids with low thermal conductivity.

Zhen Qian et al. [59] studied the effects of mass flow rate, number of channels, flow direction and width of channels on the performance of mini-channel cold plates. The results show that by increasing the number of cooling channels the thermal performance of cold plates is increasing however when the number of channels is more than five there are no significant advantages.

Tao Deng et al. [60] investigated a battery pack consisting of 4 batteries and 5 cold plates. They have studied the effects of mass flow rate, number of cold plates, cooling channel distribution and cooling direction. The results show that heat accumulates easily in the middle of the battery, therefore a greater number of cold plates should be arranged as close as possible to the middle of the battery pack. They have also observed that cooling direction of channels in the cold plate also can increase the temperature uniformity of battery pack. Yuqi Huang et al. [61] introduced streamlined shape for cold plate channels and the results show that because of streamlined shape resistance to flow was reduced resulting in reduction thereby increasing the heat exchanger efficiency. They have also observed that because of streamlined shape temperature uniformity of cold plate also increased. Panchal et al. [62] studied the turbulent flow in the mini channel both numerically and experimentally. From the results it was observed that with increase in discharge rates battery temperature is increasing. It was also observed that the thermocouples which are near to the electrodes are showing high temperatures than those which are located at the center of the battery surface.

Anthony Jarrett et al. [63] done parametric study on serpentine mini channel cold plate by varying parameters like width of channel and position of channel. Huan-ling Liu et al. [64] and Tao Deng et al. [65] used tree type and leaf type mini channels respectively and found better results than regular rectangular channel.

4.3. Thermoelectric BTMS

Thermoelectric cooler which works on the Peltier effect can also be used for the thermal management of batteries in the electric vehicles as shown Fig.8. It consists of P-semiconductor and N-semiconductor. The sides of semiconductor are attached to a ceramic sheet having high thermal conductivity. Because of Peltier effect when current flows from N to P semiconductors which results in refrigeration effect on the ceramic sheet and when the current flows from P to N semiconductors exothermic reaction occurs on the fins. Thermoelectric cooler when kept adjacent to the battery module, it can transfer the heat generated in the battery to the other side of thermoelectric cooler [66].

Xinxi Li [66] designed a BTMS based on thermoelectric cooler coupled with forced convection and compared natural convection cooling, forced convection cooling and thermoelectric cooling. Results reveals that thermoelectric cooling is the best cooling because it not only decreasing the maximum temperature of battery but also reducing the power consumption. Lyu et al. [67] developed a BTMS which is combination of liquid cooling, air cooling and thermoelectric cooling. From the results it is observed that the batteries surface temperature was decreased from 55^0C to 43^0C . Chakib Alaoui [68] developed a solid-state battery thermal management system based on thermoelectric cooler and that was installed in an electric vehicle that was driven in US06 cycle. The performance of the BTMS was found satisfactory. Changsheng Qiu et al. [69] presented BTMS based on thermoelectric cooler with varying cross section and have optimized the geometric structure. The results show that for an optimized thermoelectric cooler with a varying cross section the coefficient of performance was improved by 21.59% and the cooling capacity was improved by 35.73% compared to that with a constant cross section. Yong Liu et al. [70] used thermoelectric cooler for battery thermal management and results have shown that it can be used not only to cool the battery but also to heat the battery when ambient temperatures are too low in winter. Although some amount of research is conducted on thermoelectric based BTMS much more study is to be done in the future [10].

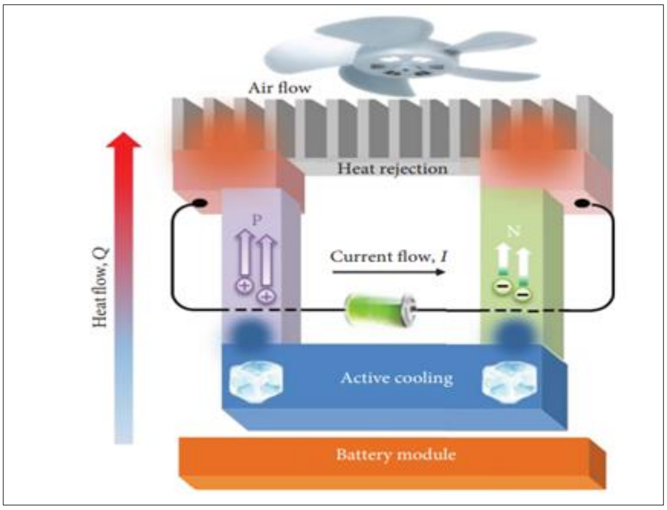

Figure 8 Thermoelectric BTMS [66]

4.4. Phase Change Materials (PCMs) based BTMS

PCMs are latent heat storage materials which store energy during phase change from solid to liquid and absorb energy during phase change from liquid to solid [71]. They utilize the latent heat for phase change almost at constant temperature. Therefore, they can be used for heating and cooling in BTMS. PCMs can be classified as gas to liquid, solid to gas, solid to solid, and solid to liquid PCMs. The latent energy in gas to liquid phase transition is generally greater than that in the solid to liquid phase transition but the gas to liquid phase change is not much practical due to the higher volume expansion. The solid to gas phase transition is also impractical because it needs substantial latent energy. Due to high phase change temperature solid to solid PCMs are not used much. Solid to liquid PCMs are the most commonly used type because they have large latent heat storage capacity and small volume changes during the phase change [72].

PCM based BTMS does not require any additional components and it can effectively reduce the batteries maximum temperature, maximum temperature difference among cells inside the battery pack but its application is limited because of mass. Paraffin, wax and composite materials are the most commonly used PCMs [73].

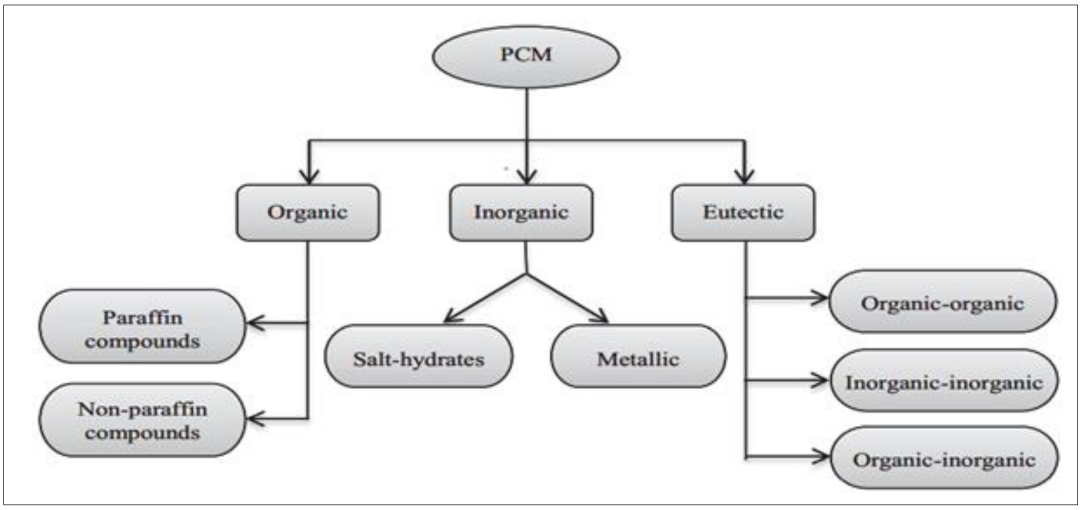

Figure 9 Classification of solid to liquid transition PCMs [75]

Solid to liquid PCMs can be further classified as organic, inorganic or eutectic as shown in Fig.9. Organic PCM is a combination of hydrocarbon chains. Paraffin is an example of organic PCM. Inorganic PCMs are salt hydrates which contains metallic elements such as di-sodium hydrogen phosphate do-decahydrate. Eutectic PCM is a combination of organic PCM and inorganic PCM. Cooper Foam combined with Paraffin wax is an example of eutectic PCM [74].

Mengyao Lu et al. [76] proposed a BTMS by incorporating paraffin wax as PCM and the results shows that the temperature is more uniform while using PCM compared to natural or forced convection cooling by using air. Javani et al. [77] studied PCM based BTMS by varying the thickness of PCM around cells. The results show that by increasing the thickness of PCM the maximum temperature is getting decreased whereas more temperature uniformity is obtained when the thickness is low.

Duan et al. [78] investigated PCM with two designs by inserting PCM cylinder and PCM jacket around the cell. They found that both the designs were effective in thermal management of battery.

Yutao Huo et al.[79] studied the effect of latent heat of PCM and they observed that the high latent heat of PCM is more effective at both high ambient temperatures and low ambient temperatures .Ziye Ling et al. [80] studied the effects of phase change temperature of PCM and the results shows that PCMs too high or too low phase temperatures are not effective, and they suggested that the phase change temperature of PCM should be in the range of 40 ∘ C to 45 ∘ C .

Even though PCM based BTMS is an excellent passive technique, but it has some limitations like low thermal conductivity, difference in volume, high flammability, leakage problems, disposal, and flowability. Therefore, to overcome these limitations thermal conductivity enhancers are used in PCM based BTMS [77]. Carbon-based and metal-based additives are the most commonly used thermal conductivity enhancers. PCMs with thermal conductivity enhancers are called composite PCMs [10]. Riza Kizilel et al. [81] developed a composite PCM based BTMS by adding expanded graphite as thermal conductivity enhancer and compared with natural, forced convection air cooling BTMS. The results show that PCM based BTMS can be an effective alternative to forced convection air cooling BTMS and allows a much-simplified cooling design for electric vehicles.

Babapoor et al. [82] added carbon fibers as a thermal conductivity enhancer and have studied the effects of carbon fiber size, percentage of carbon fiber weight on the thermal management of batteries. The results have shown that by adding 0.46% of mass and 2mm long carbon fibers and PCM we are obtaining the best performance.

Pradyumna Goli et al. [83] used graphene to the hydrocarbon based PCM to enhance the thermal conductivity and they observed that by incorporating graphene thermal conductivity got increased more than double margin without losing its latent heat storage capability.

Jiangyun Zhang et al. [84] added metal based additive aluminum nitride as a thermal conductivity enhancer and investigated this PCM based BTMS by varying the mass fractions of aluminum nitride. The results have shown that optimum mass fraction of aluminum is 20%. In addition, they have also compared this BTMS with air based BTMS and the results shows that PCM based BTMS with aluminum nitride as an additive provides much better performance compared to air based BTMS.

Amine Lazrak et al. [85] studied the combination of PCM with metal mesh and compared this BTMS with pure PCM based BTMS. The results show compared to pure PCM based BTMS the proposed composite PCM based BTMS is decreasing maximum temperature of battery by 10 ∘ C more . Gholamreza Karimi et al. [86] studied three different nanoparticles Ag, Cu, Fe_3O_4 as thermal conductivity enhancers and the results shows that the Ag particles have shown the best thermal performance.

4.5. Heat Pipe based BTMS

A heat pipe is a device which is sealed with vacuum in which we fill the working fluid which transfers heat during phase change from liquid to vapor as shown in Fig.10. The heat pipe consists of evaporating section, condensing section and adiabatic section. If we keep the evaporator section in contact with the battery module the working fluid inside the heat pipe absorbs the heat from the module and it gets evaporated. Because of the pressure gradient [developed because of high vapour pressure and lower molecular density of vapour] this working fluid in the form of vapour moves towards the condensing section and rejects to heat to the atmosphere in the condenser section. After rejecting heat, the vapour will be condensed into liquid form. Because of capillary forces the liquid will again come back to the evaporator and repeats the cycle [89,10]. The heat pipe based BTMS is an emerging passive cooling technique with low cost and high thermal conductivity. It is lightweight with a long lifetime [87]. Heat can be automatically transferred from battery cells to cold sources because of evaporation and condensation inside the heat pipe [88].

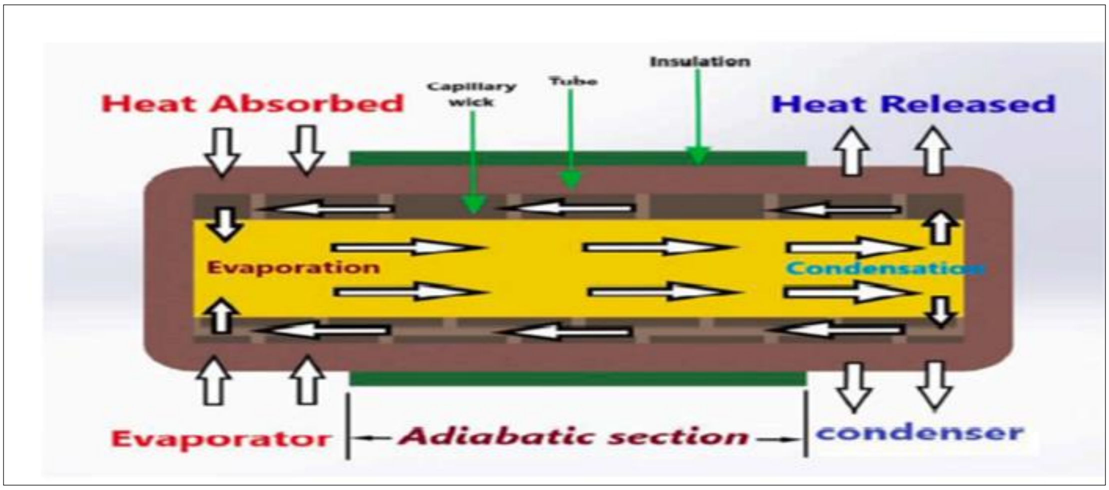

Figure 10 Working of heat pipe [1]

Thanh-Ha Tran et al. [90] studied the effects of placement of heat pipe on the performance of heat pipe based BTMS and has observed better performance when the heat pipe is placed vertically. Rui Zhao et al. [91] investigated heat pipe based BTMS with several cooling techniques like only heat pipe, heat pipe with wet cooling, and heat pipe with fans. They have observed better results while using heat pipe with wet cooling. They have also stated that the combination of air cooling with the wet cooling of the condenser section of the heat pipe was the best method.

Zhonghao Rao et al. [92,] developed a flat shaped copper heat pipe. They have studied the performance at different heat generation rates and different positions of the heat pipe. Zhonghao Rao et al. [93] also designed an oscillating heat pipe based BTMS with horizontal and vertical positions of oscillating heat pipe. They obtained maximum temperature difference of cell as 7^0C with vertical arrangement and 10^0C with horizontal arrangement.

5. Hybrid BTMS

After comparison we can say that every BTMS has its own advantages and disadvantages. Therefore, research is focusing on a combination of active and passive BTMS or both passive BTMSs to improve the efficiency of BTMS. The liquid based BTMS have good thermal conductivity, but it needs extra power to run the pump. If PCM also with liquid based BTMS are used, it would reduce the pump size. The combination of two or more BTMSs is known as hybrid BTMS [94]. Hassan Fathabadi [95] designed a hybrid BTMS which is a combination of Air and PCM based BTMS, and the results show that with excellent thermal performance the maximum temperature remained in the recommended temperature range. Yiran Zheng et al. [96] designed a hybrid BTMS with active liquid cooling and PCM based BTMS. They have studied a battery pack consisting of 110 cells and 8 flow tubes which are surrounded by PCM. Coolant flows through the flow tubes. With this hybrid based BTMS they have obtained maximum temperature of 38.69 ∘ C and the maximum temperature difference of 2.23 ∘ C which is very much acceptable. Yanqi Zhao et al. [97] proposed a hybrid BTMS which is a combination of two passive BTMSs, PCM based, and heat pipe based BTMSs. They have compared the performance of BTMS while using only air cooling, only PCM cooling, and the combination of PCM and heat pipe cooling. The results show that the proposed hybrid BTMS have more efficiency compared to only PCM cooling or only air cooling.

6. Conclusion

Though the petroleum derived fuel run vehicles have been serving the nations both for human and goods transportation for nearly two centuries. However, owing to difficulties of dependence on other counties for import of fuels and harmful emissions generated are forcing the nations to shift swiftly to electric mobility. Even though for countries like India and other developing countries, immediate switch over to neat electric vehicles is still far away but hybrid vehicles could be better solution to circumvent issues of fuel crisis and pollution related issues. Many countries have slowly shifting either neat electric vehicles, or fuel cell run vehicles or battery run vehicles. The paper presented over view of use of batteries in electric vehicles and among various types, lithium-ion batteries are preferred ones due its high specific energy and light weight, have become major source for almost all variants of electric vehicles. Due to its usage being exposed to different operating conditions and ambient, Thermal runway has become major cause of hazardous accidents. Proper thermal management is essential to maintain lithium ion battery in the range of 15 °C to 40 °C with temperature difference among cells inside the battery pack less than 5 °C, for majority of regions of Indian terrain. Between internal and external thermal management systems, external system is more preferable. With air cooling unit has emerged as effective.

Compliance with ethical standards

Acknowledgments

The authors are highly grateful to the authorities of National Institute of Technology Warangal, especially for the Department of Mechanical Engineering, for providing support for reference of literature through e-journals.

Disclosure of conflict of interest

The author(s) certify that they have No Conflict of Interest in the subject matter or materials discussed in this manuscript.

References

[1] Shahjalal M, Shams T, Islam ME, Alam, W, Modak, M. Hossain, S. bin, Ramadesigan, V, Ahmed, MR., Ahmed H, and Iqbal, A. (2021). A review of thermal management for Li-ion batteries: Prospects, challenges, and issues. In Journal of Energy Storage, 39, Elsevier Ltd. https://doi.org/10.1016/j.est.2021.102518.

[2] Amba Prasad Rao, G and Karthikeya Sharma, T (2020). Engine Emission Control Technologies, Apple Academic Press (CRC), Taylor and Francis Group.

[3] Liu, H., Wei, Z., He, W., and Zhao, J. (2017). Thermal issues about Li-ion batteries and recent progress in battery thermal management systems: A review. In Energy Conversion and Management, 150, 304–330). Elsevier Ltd. https://doi.org/10.1016/j.enconman.2017.08.016

[4] Lin, J., Liu, X., Li, S., Zhang, C., and Yang, S. (2021). A review on recent progress, challenges and perspective of battery thermal management system. In International Journal of Heat and Mass Transfer (Vol. 167). Elsevier Ltd. https://doi.org/10.1016/j.ijheatmasstransfer.2020.120834

[5] Mali, V., Saxena, R., Kumar, K., Kalam, A., and Tripathi, B. (2021). Review on battery thermal management systems for energy-efficient electric vehicles. In Renewable and Sustainable Energy Reviews (Vol. 151). Elsevier Ltd. https://doi.org/10.1016/j.rser.2021.111611

[6] Arora, S. (2018). Selection of thermal management system for modular battery packs of electric vehicles: A review of existing and emerging technologies. Int. Journal of Power Sources (Vol. 400, pp. 621–640). Elsevier B.V. https://doi.org/10.1016/j.jpowsour.2018.08.020

[7] Ma, S., Jiang, M., Tao, P., Song, C., Wu, J., Wang, J., Deng, T., and Shang, W. (2018). Temperature effect and thermal impact in lithium-ion batteries: A review. In Progress in Natural Science: Materials International (Vol. 28, Issue 6, pp. 653–666). Elsevier B.V. https://doi.org/10.1016/j.pnsc.2018.11.002

[8] Yue, Q. L., He, C. X., Wu, M. C., and Zhao, T. S. (2021). Advances in thermal management systems for next-generation power batteries. In International Journal of Heat and Mass Transfer (Vol. 181). Elsevier Ltd. https://doi.org/10.1016/j.ijheatmasstransfer.2021.121853

[9] Amine, K., Liu, J., and Belharouak, I. (2005). High-temperature storage and cycling of C-LiFePO4/graphite Li-ion cells. Electrochemistry Communications, 7(7), 669–673. https://doi.org/10.1016/j.elecom.2005.04.018

[10] Patel, J. R., and Rathod, M. K. (2020). Recent developments in the passive and hybrid thermal management techniques of lithium-ion batteries. In Journal of Power Sources (Vol. 480). Elsevier B.V. https://doi.org/10.1016/j.jpowsour.2020.228820 10

[11] Motloch, C., Christophersen, J., Belt, J., Wright, R. et al., "High-Power Battery Testing Procedures and Analytical Methodologies for HEV's," SAE Technical Paper 2002-01-1950, 2002, https://doi.org/10.4271/2002-01-1950.

[12] Feng, X., Xu, C., He, X., Wang, L., Zhang, G., and Ouyang, M. (2018). Mechanisms for the evolution of cell variations within a LiNixCoyMnzO2/graphite lithium-ion battery pack caused by temperature non-uniformity. Journal of Cleaner Production, 205, 447–462. https://doi.org/10.1016/j.jclepro.2018.09.003

[13] Tete, P. R., Gupta, M. M., and Joshi, S. S. (2021). Developments in battery thermal management systems for electric vehicles: A technical review. In Journal of Energy Storage (Vol. 35). Elsevier Ltd. https://doi.org/10.1016/j.est.2021.102255

[14] Rao, Z., and Wang, S. (2011). A review of power battery thermal energy management. In Renewable and Sustainable Energy Reviews (Vol. 15, Issue 9, pp. 4554–4571). https://doi.org/10.1016/j.rser.2011.07.096

[15] Yang, L., Zhou, F., Sun, L., and Wang, S. (2022). Thermal management of lithium-ion batteries with nanofluids and nano-phase change materials: a review. Journal of Power Sources, 539. https://doi.org/10.1016/j.jpowsour.2022.231605

[16] Chan, C., Peng, H., Liu, G. et al. (2008). High-performance lithium battery anodes using silicon nanowires. Nature Nanotech 3, 31–35 https://doi.org/10.1038/nnano.2007.41

[17] Sheu, S. P., Yao, C. Y., Chen, J. M., and Chiou, Y. C. (1997). SOURCES Influence of the $LiCoO_2$ particle size on the performance of lithium-ion batteries. In Journal of Power Sources,68.

[18] Lu, W., Jansen, A., Dees, D., Nelson, P., Veselka, N. R., and Henriksen, G. (2011). High-energy electrode investigation for plug-in hybrid electric vehicles. Journal of Power Sources, 196(3), 1537–1540. https://doi.org/10.1016/j.jpowsour.2010.08.117

[19] Xiang Gao, Wenquan Lu, JunXu. (2021). Unlocking multiphysics design guidelines on Si/C composite nanostructures for high-energy-density and robust lithium-ion battery anode. Nano Energy, 81, https://doi.org/10.1016/j.nanoen.2020.105591

[20] Yang, J., Wang, J., Wang, D., Li, X., Geng, D., Liang, G., Gauthier, M., Li, R., and Sun, X. (2012). 3D porous LiFePO 4/graphene hybrid cathodes with enhanced performance for Li-ion batteries. Journal of Power Sources, 208, 340–344. https://doi.org/10.1016/j.jpowsour.2012.02.032

[21] Park, H. (2013). A design of air flow configuration for cooling lithium ion battery in hybrid electric vehicles. Journal of Power Sources, 239, 30–36. https://doi.org/10.1016/j.jpowsour.2013.03.102

[22] Pesaran, Ahmad. (2001). Battery Thermal Management in EVs and HEVs: Issues and Solutions. Battery Man. 43. https://www.researchgate.net/publication/237250969

[23] Lu, M., Zhang, X., Ji, J., Xu, X., and Zhang, Y. (2020). Research progress on power battery cooling technology for electric vehicles. In Journal of Energy Storage (Vol. 27). Elsevier Ltd. https://doi.org/10.1016/j.est.2019.101155

[24] Wang, Q., Jiang, B., Li, B., and Yan, Y. (2016). A critical review of thermal management models and solutions of lithium-ion batteries for the development of pure electric vehicles. In Renewable and Sustainable Energy Reviews (Vol. 64, pp. 106–128). Elsevier Ltd. https://doi.org/10.1016/j.rser.2016.05.033

[25] Rao, Z., and Wang, S. (2011). A review of power battery thermal energy management. In Renewable and Sustainable Energy Reviews (Vol. 15, Issue 9, pp. 4554–4571). https://doi.org/10.1016/j.rser.2011.07.096

[26] Sharma, D. K., and Prabhakar, A. (2021). A review on air cooled and air centric hybrid thermal management techniques for Li-ion battery packs in electric vehicles. In Journal of Energy Storage (Vol. 41). Elsevier Ltd. https://doi.org/10.1016/j.est.2021.102885

[27] Wang, Y., Liu, B., Han, P., Hao, C., Li, S., You, Z., and Wang, M. (2021). Optimization of an air-based thermal management system for lithium-ion battery packs. Journal of Energy Storage, 44. https://doi.org/10.1016/j.est.2021.103314

[28] Kim, G. H., and Pesaran, A. (2006). Battery Thermal Management System Design Modeling. http://www.osti.gov/bridge

[29] Yu, K., Yang, X., Cheng, Y., and Li, C. (2014). Thermal analysis and two-directional air flow thermal management for lithium-ion battery pack. Journal of Power Sources, 270, 193–200. https://doi.org/10.1016/j.jpowsour.2014.07.086

[30] Xu, X. M., and He, R. (2013). Research on the heat dissipation performance of battery pack based on forced air cooling. Journal of Power Sources, 240, 33–41. https://doi.org/10.1016/j.jpowsour.2013.03.004

[31] Cen, J., and Jiang, F. (2020). Li-ion power battery temperature control by a battery thermal management and vehicle cabin air conditioning integrated system. Energy for Sustainable Development, 57, 141–148. https://doi.org/10.1016/j.esd.2020.06.004

[32] Xie, J., Ge, Z., Zang, M., and Wang, S. (2017). Structural optimization of lithium-ion battery pack with forced air cooling system. Applied Thermal Engineering, 126, 583–593. https://doi.org/10.1016/j.applthermaleng.2017.07.143

[33] Fan, L., Khodadadi, J. M., and Pesaran, A. A. (2013). A parametric study on thermal management of an air-cooled lithium-ion battery module for plug-in hybrid electric vehicles. Journal of Power Sources, 238, 301–312. https://doi.org/10.1016/j.jpowsour.2013.03.050

[34] Zhang, F., Lin, A., Wang, P., and Liu, P. (2021). Optimization design of a parallel air-cooled battery thermal management system with spoilers. Applied Thermal Engineering, 182. https://doi.org/10.1016/j.applthermaleng.2020.116062

[35] Pesaran, A. A. (2002). Battery thermal models for hybrid vehicle simulations Journal of Power Sources, 110(2), 377-382.

[36] Xun, J., Liu, R., and Jiao, K. (2013). Numerical and analytical modeling of lithium ion battery thermal behaviors with different cooling designs. Journal of Power Sources, 233, 47–61. https://doi.org/10.1016/j.jpowsour.2013.01.095

[37] Westbrook, Michael Hereward. (2001)The Electric Car: Development and future of battery, hybrid and fuel-cell cars. No. 38. Iet,.

[38] Wu, S., Lao, L., Wu, L., Liu, L., Lin, C., and Zhang, Q. (2022). Effect analysis on integration efficiency and safety performance of a battery thermal management system based on direct contact liquid cooling. Applied Thermal Engineering, 201. https://doi.org/10.1016/j.applthermaleng.2021.117788

[39] Zhao, G., Wang, X., Negnevitsky, M., and Zhang, H. (2021). A review of air-cooling battery thermal management systems for electric and hybrid electric vehicles. In Journal of Power Sources (Vol. 501). Elsevier B.V. https://doi.org/10.1016/j.jpowsour.2021.230001

[40] Wu, W., Wang, S., Wu, W., Chen, K., Hong, S., and Lai, Y. (2019). A critical review of battery thermal performance and liquid based battery thermal management. In Energy Conversion and Management (Vol. 182, pp. 262–281). Elsevier Ltd. https://doi.org/10.1016/j.enconman.2018.12.051

[41] Jiaqiang, E., Xu, S., Deng, Y., Zhu, H., Zuo, W., Wang, H., Chen, J., Peng, Q., and Zhang, Z. (2018). Investigation on thermal performance and pressure loss of the fluid cold-plate used in thermal management system of the battery pack. Applied Thermal Engineering, 145, 552–568. https://doi.org/10.1016/j.applthermaleng.2018.09.048

[42] Park, S., and Jung, D. (2013). Battery cell arrangement and heat transfer fluid effects on the parasitic power consumption and the cell temperature distribution in a hybrid electric vehicle. Journal of Power Sources, 227, 191–198. https://doi.org/10.1016/j.jpowsour.2012.11.039

[43] Saw, L. H., Tay, A. A. O., and Zhang, L. W. (2015). Thermal management of lithium-ion battery pack with liquid cooling. Annual IEEE Semiconductor Thermal Measurement and Management Symposium, 2015-April, 298–302. https://doi.org/10.1109/SEMI-THERM.2015.7100176

[44] Zhao, C., Zhang, B., Zheng, Y., Huang, S., Yan, T., and Liu, X. (2020). Hybrid battery thermal management system in electrical vehicles: A review. Energies, 13(23). https://doi.org/10.3390/en13236257

[45] Al-Zareer, M., Dincer, I., and Rosen, M. A. (2017). Electrochemical modeling and performance evaluation of a new ammonia-based battery thermal management system for electric and hybrid electric vehicles. Electrochimica Acta, 247, 171–182. https://doi.org/10.1016/j.electacta.2017.06.162

[46] Al-Zareer, M., Dincer, I., and Rosen, M. A. (2017). Novel thermal management system using boiling cooling for high-powered lithium-ion battery packs for hybrid electric vehicles. Journal of Power Sources, 363, 291–303. https://doi.org/10.1016/j.jpowsour.2017.07.067

[47] Liu, J., Fan, Y., and Xie, Q. (2022). Feasibility study of a novel oil-immersed battery cooling system: Experiments and theoretical analysis. Applied Thermal Engineering, 208. https://doi.org/10.1016/j.applthermaleng.2022.118251

[48] Guo, Z., Xu, J., Xu, Z., Mubashir, M., Wang, H., and Mei, X. (2022). A Lightweight Multichannel Direct Contact Liquid-Cooling System and Its Optimization for Lithium-Ion Batteries. IEEE Transactions on Transportation Electrification, 8(2), 2334–2345. https://doi.org/10.1109/TTE.2021.3131718

[49] Van Gils, R. W., Danilov, D., Notten, P. H. L., Speetjens, M. F. M., and Nijmeijer, H. (2014). Battery thermal management by boiling heat-transfer. Energy Conversion and Management, 79, 9–17. https://doi.org/10.1016/j.enconman.2013.12.006

[50] Xia, G., Cao, L., and Bi, G. (2017). A review on battery thermal management in electric vehicle application. In Journal of Power Sources, 367, 90–105. https://doi.org/10.1016/j.jpowsour.2017.09.046

[51] Chen, D., Jiang, J., Kim, G. H., Yang, C., and Pesaran, A. (2016). Comparison of different cooling methods for lithium ion battery cells. Applied Thermal Engineering, 94, 846–854. https://doi.org/10.1016/j.applthermaleng.2015.10.015

[52] Jin, L. W., Lee, P. S., Kong, X. X., Fan, Y., and Chou, S. K. (2014). Ultra-thin mini-channel LCP for EV battery thermal management. Applied Energy, 113, 1786–1794. https://doi.org/10.1016/j.apenergy.2013.07.013

[53] Amalesh, T., and Narasimhan, N. L. (2020). Introducing new designs of mini-channel cold plates for the cooling of Lithium-ion batteries. Journal of Power Sources, 479. https://doi.org/10.1016/j.jpowsour.2020.228775

[54] Zuo, S., Chen, S., and Yin, B. (2022). Performance analysis and improvement of lithium-ion battery thermal management system using mini-channel cold plate under vibration environment. International Journal of Heat and Mass Transfer, 193. https://doi.org/10.1016/j.ijheatmasstransfer.2022.122956

[55] Deng, T., Zhang, G., and Ran, Y. (2018). Study on thermal management of rectangular Li-ion battery with serpentine-channel cold plate. International Journal of Heat and Mass Transfer, 125, 143–152. https://doi.org/10.1016/j.ijheatmasstransfer.2018.04.065

[56] Sheng, L., Su, L., Zhang, H., Li, K., Fang, Y., Ye, W., and Fang, Y. (2019). Numerical investigation on a lithium ion battery thermal management utilizing a serpentine-channel liquid cooling plate exchanger. International Journal of Heat and Mass Transfer, 141, 658–668. https://doi.org/10.1016/j.ijheatmasstransfer.2019.07.033

[57] Huo, Y., Rao, Z., Liu, X., and Zhao, J. (2015). Investigation of power battery thermal management by using mini-channel cold plate. Energy Conversion and Management, 89, 387–395. https://doi.org/10.1016/j.enconman.2014.10.015

[58] Liu, H., Chika, E., and Zhao, J. (2018). Investigation into the effectiveness of nanofluids on the mini-channel thermal management for high power lithium ion battery. Applied Thermal Engineering, 142, 511–523. https://doi.org/10.1016/j.applthermaleng.2018.07.037

[59] Qian, Z., Li, Y., and Rao, Z. (2016). Thermal performance of lithium-ion battery thermal management system by using mini-channel cooling. Energy Conversion and Management, 126, 622–631. https://doi.org/10.1016/j.enconman.2016.08.063

[60] Deng, T., Zhang, G., Ran, Y., and Liu, P. (2019). Thermal performance of lithium ion battery pack by using cold plate. Applied Thermal Engineering, 160. https://doi.org/10.1016/j.applthermaleng.2019.114088

[61] Huang, Y., Mei, P., Lu, Y., Huang, R., Yu, X., Chen, Z., and Roskilly, A. P. (2019). A novel approach for Lithium-ion battery thermal management with streamline shape mini channel cooling plates. Applied Thermal Engineering, 157. https://doi.org/10.1016/j.applthermaleng.2019.04.033

[62] Panchal, S., Khasow, R., Dincer, I., Agelin-Chaab, M., Fraser, R., and Fowler, M. (2017). Thermal design and simulation of mini-channel cold plate for water cooled large sized prismatic lithium-ion battery. Applied Thermal Engineering, 122, 80–90. https://doi.org/10.1016/j.applthermaleng.2017.05.010

[63] Jarrett, A., and Kim, I. Y. (2011). Design optimization of electric vehicle battery cooling plates for thermal performance. Journal of Power Sources, 196(23), 10359–10368. https://doi.org/10.1016/j.jpowsour.2011.06.090

[64] Liu, H. ling, Shi, H. bo, Shen, H., and Xie, G. (2019). The performance management of a Li-ion battery by using tree-like mini-channel heat sinks: Experimental and numerical optimization. Energy, 189. https://doi.org/10.1016/j.energy.2019.116150

[65] Deng, T., Ran, Y., Zhang, G., Chen, X., and Tong, Y. (2019). Design optimization of bifurcating mini-channels cooling plate for rectangular Li-ion battery. International Journal of Heat and Mass Transfer, 139, 963–973. https://doi.org/10.1016/j.ijheatmasstransfer.2019.05.082

[66] Li, X., Zhong, Z., Luo, J., Wang, Z., Yuan, W., Zhang, G., Yang, C., and Yang, C. (2019). Experimental Investigation on a Thermoelectric Cooler for Thermal Management of a Lithium-Ion Battery Module. International Journal of Photoenergy, 2019. https://doi.org/10.1155/2019/3725364

[67] Lyu, Y., Siddique, A. R. M., Majid, S. H., Biglarbegian, M., Gadsden, S. A., and Mahmud, S. (2019). Electric vehicle battery thermal management system with thermoelectric cooling. Energy Reports, 5, 822–827. https://doi.org/10.1016/j.egyr.2019.06.016

[68] Alaoui, C. (2013). Solid-state thermal management for lithium-ion EV batteries. IEEE Transactions on Vehicular Technology, 62(1), 98–107. https://doi.org/10.1109/TVT.2012.2214246

[69] Qiu, C., and Shi, W. (2020). Comprehensive modeling for optimized design of a thermoelectric cooler with non-constant cross-section: Theoretical considerations. Applied Thermal Engineering, 176. https://doi.org/10.1016/j.applthermaleng.2020.115384

[70] Liu, Y., Yang, S., Guo, B., and Deng, C. (2014). Numerical Analysis and Design of Thermal Management System for Lithium Ion Battery Pack Using Thermoelectric Coolers. Advances in Mechanical Engineering, 2014. https://doi.org/10.1155/2014/852712

[71] Alami, A. H., Maghrabie, H. M., Abdelkareem, M. A., Sayed, E. T., Yasser, Z., Salameh, T., Rahman, S. M. A., Rezk, H., and Olabi, A. G. (2022). Potential applications of phase change materials for batteries' thermal management systems in electric vehicles. Journal of Energy Storage, 54. https://doi.org/10.1016/j.est.2022.105204

[72] Chen, H., Zhang, T., Gao, Q., Han, Z., Xu, Y., Yang, K., Xu, X., and Liu, X. (2022). Advance and prospect of power battery thermal management based on phase change and boiling heat transfer. Journal of Energy Storage, 53, 105254. https://doi.org/10.1016/j.est.2022.105254

[73] Bais, A. R., Subhedhar, D. G., Joshi, N. C., and Panchal, S. (2022). Numerical investigation on thermal management system for lithium ion battery using phase change material. Materials Today: Proceedings, 66, 1726–1733. https://doi.org/10.1016/j.matpr.2022.05.269

[74] Zare, P., Perera, N., Lahr, J., and Hasan, R. (2022). Solid-liquid phase change materials for the battery thermal management systems in electric vehicles and hybrid electric vehicles – A systematic review. Journal of Energy Storage, 52. Elsevier Ltd. https://doi.org/10.1016/j.est.2022.105026

[75] Mitra, A., Kumar, R., Singh, D. K., and Said, Z. (2022). Advances in the improvement of thermal-conductivity of phase change material-based lithium-ion battery thermal management systems: An updated review. Journal of Energy Storage, 53. https://doi.org/10.1016/j.est.2022.105195

[76] Lu, M., Zhang, X., Ji, J., Xu, X., and Zhang, Y. (2020). Research progress on power battery cooling technology for electric vehicles. Journal of Energy Storage ,27. Elsevier Ltd. https://doi.org/10.1016/j.est.2019.101155

[77] Javani, N., Dincer, I., Naterer, G. F., and Yilbas, B. S. (2014). Heat transfer and thermal management with PCMs in a Li-ion battery cell for electric vehicles. International Journal of Heat and Mass Transfer, 72, 690–703. https://doi.org/10.1016/j.ijheatmasstransfer.2013.12.076

[78] Duan, X., and Naterer, G. F. (2010). Heat transfer in phase change materials for thermal management of electric vehicle battery modules. International Journal of Heat and Mass Transfer, 53(23–24), 5176–5182. https://doi.org/10.1016/j.ijheatmasstransfer.2010.07.044

[79] Huo, Y., and Rao, Z. (2017). Investigation of phase change material based battery thermal management at cold temperature using lattice Boltzmann method. Energy Conversion and Management, 133, 204–215. https://doi.org/10.1016/j.enconman.2016.12.009

[80] Ling, Z., Chen, J., Fang, X., Zhang, Z., Xu, T., Gao, X., and Wang, S. (2014). Experimental and numerical investigation of the application of phase change materials in a simulative power batteries thermal management system. Applied Energy, 121, 104–113. https://doi.org/10.1016/j.apenergy.2014.01.075

[81] Kizilel, R., Sabbah, R., Selman, J. R., and Al-Hallaj, S. (2009). An alternative cooling system to enhance the safety of Li-ion battery packs. Journal of Power Sources, 194(2), 1105–1112. https://doi.org/10.1016/j.jpowsour.2009.06.074

[82] Babapoor, A., Azizi, M., and Karimi, G. (2015). Thermal management of a Li-ion battery using carbon fiber-PCM composites. Applied Thermal Engineering, 82, 281–290. https://doi.org/10.1016/j.applthermaleng.2015.02.068

[83] Goli, P., Legedza, S., Dhar, A., Salgado, R., Renteria, J., and Balandin, A. A. (2014). Graphene-enhanced hybrid phase change materials for thermal management of Li-ion batteries. Journal of Power Sources, 248, 37–43. https://doi.org/10.1016/j.jpowsour.2013.08.135

[84] Zhang, J., Li, X., Zhang, G., Wang, Y., Guo, J., Wang, Y., Huang, Q., Xiao, C., and Zhong, Z. (2020). Characterization and experimental investigation of aluminum nitride-based composite phase change materials for battery thermal management. Energy Conversion and Management, 204. https://doi.org/10.1016/j.enconman.2019.112319

[85] Lazrak, A., Fourmigué, J. F., and Robin, J. F. (2018). An innovative practical battery thermal management system based on phase change materials: Numerical and experimental investigations. Applied Thermal Engineering, 128, 20–32. https://doi.org/10.1016/j.applthermaleng.2017.08.172

[86] Karimi, G., Azizi, M., and Babapoor, A. (2016). Experimental study of a cylindrical lithium ion battery thermal management using phase change material composites. Journal of Energy Storage, 8, 168–174. https://doi.org/10.1016/j.est.2016.08.005

[87] Babu Sanker, S., and Baby, R. (2022). Phase change material based thermal management of lithium ion batteries: A review on thermal performance of various thermal conductivity enhancers. In Journal of Energy Storage (Vol. 50). Elsevier Ltd. https://doi.org/10.1016/j.est.2022.104606.

[88] Mbulu, H., Laoonual, Y., and Wongwises, S. (2021). Experimental study on the thermal performance of a battery thermal management system using heat pipes. Case Studies in Thermal Engineering, 26. https://doi.org/10.1016/j.csite.2021.101029

[89] Liang, Z., Wang, R., Malt, A. H., Souri, M., Esfahani, M. N., and Jabbari, M. (2021). Systematic evaluation of a flat-heat-pipe-based thermal management: Cell-to-cell variations and battery ageing. Applied Thermal Engineering, 192. https://doi.org/10.1016/j.applthermaleng.2021.116934

[90] Tran, T. H., Harmand, S., and Sahut, B. (2014). Experimental investigation on heat pipe cooling for Hybrid Electric Vehicle and Electric Vehicle lithium-ion battery. Journal of Power Sources, 265, 262–272. https://doi.org/10.1016/j.jpowsour.2014.04.130

[91] Zhao, R., Gu, J., and Liu, J. (2015). An experimental study of heat pipe thermal management system with wet cooling method for lithium ion batteries. Journal of Power Sources, 273, 1089–1097. https://doi.org/10.1016/j.jpowsour.2014.10.007

[92] Rao, Z., Wang, S., Wu, M., Lin, Z., and Li, F. (2013). Experimental investigation on thermal management of electric vehicle battery with heat pipe. Energy Conversion and Management, 65, 92–97. https://doi.org/10.1016/j.enconman.2012.08.014

[93] Rao, Z., Huo, Y., and Liu, X. (2014). Experimental study of an OHP-cooled thermal management system for electric vehicle power battery. Experimental Thermal and Fluid Science, 57, 20–26. https://doi.org/10.1016/j.expthermflusci.2014.03.017

[94] Jaguemont, J., and van Mierlo, J. (2020). A comprehensive review of future thermal management systems for battery-electrified vehicles. In Journal of Energy Storage (Vol. 31). Elsevier Ltd. https://doi.org/10.1016/j.est.2020.101551

[95] Fathabadi, H. (2014). High thermal performance lithium-ion battery pack including hybrid active-passive thermal management system for using in hybrid/electric vehicles. Energy, 70, 529–538. https://doi.org/10.1016/j.energy.2014.04.046

[96] Zheng, Y., Shi, Y., and Huang, Y. (2019). Optimisation with adiabatic interlayers for liquid-dominated cooling system on fast charging battery packs. Applied Thermal Engineering, 147, 636–646. https://doi.org/10.1016/j.applthermaleng.2018.10.090

[97] Zhao, Y., Zou, B., Li, C., and Ding, Y. (2019). Active cooling based battery thermal management using composite phase change materials. Energy Procedia, 158, 4933–4940. https://doi.org/10.1016/j.egypro.2019.01.697