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Critical review on battery thermal management and role of nanomaterial in heat transfer enhancement for electrical vehicle application

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ABSTRACT

The major issue with Lithium-ion batteries is their sensitivity to temperature. Lithium-ion cells do not perform efficiently at extreme temperature and adverse operating conditions, which can lead to thermal runaway of the battery pack. Lithium-ion batteries need to be thermally controlled within their working temperature range for their long-term durability and vehicle performance. This paper provides a review of different types of cooling strategies used in thermal management of the battery pack. Air-based, liquid-based, and Phase Change Material (PCM) based cooling methods are reviewed in this paper. Different types of battery pack arrangements as well as various heat generation methods are also reviewed. This study also presents a review of the use of nanomaterials to reduce the thermal issues of the battery pack. This paper highlights the use of nanomaterial to enhance the thermal conductivity of coolant (Phase Change Material as well as liquid coolant) used to bring the temperature of batteries in its optimum working range.

1. Introduction

Twenty-first century is known for its massive growth and technological development in the world. But this development was attained at the cost of depletion of fossil fuels and increasing greenhouse gases in the environment. Mikael Hook et al. [1] explained the impact of the rapid consumption of fossil fuels, and the rising level of greenhouse gases on climate change. The seriousness of these issues led to the utilization of electric battery-based vehicles as a new mode of transportation because these types of vehicles are energy-efficient and have environment-friendly characteristics [2]. It is estimated that the penetration of electric vehicles (EVs) will help in a significant reduction of carbon dioxide emissions by the next decade [3,4]. The market for EVs in 2016 was about 2% in global share and it is expected to reach about 22% by 2030 [5]. The driving force and source of energy behind running these EVs are batteries, therefore batteries in these novel vehicles perform the same role as that of fossil fuels in conventional vehicles. Different types of batteries can be utilized in EVs based on their merits such as Nickel Metal Hydride, Lithium-ion (Li-ion), Molten salt, Lead-acid, and Lithium Sulphur [6]. Among all rechargeable batteries available, Li-ion batteries have the highest specific energy and specific power [7]. These batteries have a longer service life, and environment-friendliness [8]. The inevitable market shift toward Li-ion batteries was enhanced by the emergence of Tesla Model S, Nissan Leaf, VW E Golf, Hyundai Ioniq, and Renault Twizzy models by automotive companies [6]. Apart from the application of Li-ion batteries in EVs, their utilization is also prevalent in laptops, cell phones, and medical equipment [9]. Despite having several utilities, Li-ion batteries have certain limitations, like degradation when operated at high temperature and requirement of effective protection of pyrophoric lithium from oxygen that released at cathode electrode during battery operation [10]. M. Brandl et al. [11] further described the problems that arises while monitoring batteries due to changes in cell chemistries with passage of time. Issues at the battery cells, modules, and pack level are resolved by a multifunctional system, that is Battery Management System (BMS), this system ensures the proper functioning of battery cells and predicts the status of the battery, communication between different battery components and maintain prolonged battery life [12]. Based upon the different literature reviews temperature range for Li-ion batteries to perform optimally varies from 25-40°C [13]. Zhao et al. [14] showed the challenges of the use of Li-ion batteries due to high temperature rise and their impact on performance, degradation of the battery pack,

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overheating issues, and thermal runaway situation. Therefore, to increase the life of batteries and to use to effectively, proper Battery Thermal Management System (BTMS) has to be deployed. For proper and safe working of batteries, it becomes essential to remove excess heat and keep the temperature of the battery pack within the optimum working range and maintain uniform temperature distribution within battery cells [15]. Efforts have been put to develop different cooling methods for the thermal management of batteries. Lazrak et al. [16] and several other researchers have discussed air, liquid, and Phase change materials (PCM) based cooling methods for optimum performance of the battery pack. As suggested by researchers, the effectiveness of the air-cooling method can be enhanced by choosing optimum inter-cell distance and forced entry of air in the system [17–19]. But due to the low thermal conductivity of air, the air cooling method is not preferred at high ambient temperature regions. EVs popularly incorporate liquid coolant for cooling due to adequate cooling performance but this cooling method has several limitations such as complexity in design and possibility of the hazardous situation due to liquid leakage as the liquid is directly exposed in close vicinity of batteries. Hence proper designing of liquid cooling system should be done, that often lead to increased overall weight and cost of the vehicle [20,21]. Air cooling and liquid cooling system have another disadvantage, i.e. more complexity in the design due to the presence of fan and pumps in the system [22]. To deal with the challenges in these traditional cooling techniques, a passive cooling method with PCM can be used. PCM based cooling methods have several advantages over other coolants such as high latent heat storing capacity, from which it can absorb heat without temperature rise during phase change process. But the main problem in the application of pure PCM (PCM with no additives such as paraffin) is low thermal conductivity which limits its application. Low thermal conductivity of both liquid and pure PCM needs to be enhanced for proper application of these coolants in thermal management systems. Shortcomings of these coolants led to the need for alternative methods to improve BTMS. Wiriyasart et al. [23] suggested the use of nanomaterial in the BTMS to enhance the thermal properties of coolant for the effective transfer of excess heat from the battery pack.

From the literature review [13–18,21,24], it was identified that many researchers studied the possible methods for battery thermal management. Previous review studies [20,22,25–29] have shown the strategies undertaken by different researchers for the thermal management of batteries such as air, liquid, and PCM based cooling methods. It was also observed from previous literature review studies [20,23,28,30] that for the effective thermal management different approach other than traditional cooling approach needs to be taken. These studies marked the possible shortcomings of traditional cooling methods and proposed a few new techniques to enhance the cooling effectiveness. Although, few review studies were done on the heat transfer enhancement of coolants but these studies were focused on the particular coolant. However, a comprehensive review needs to be done which presents the use of nanomaterial in all possible cooling strategies for thermal performance enhancement and its application in BTMS.

This review study presented here solves all the previous mentioned issues and combines various cooling strategies such as Air, Liquid, and PCM based cooling methods, for the effective development of BTMS. The different possibilities of cooling performance enhancement of these common strategies are reviewed in the study presented here. The review presented here is focused on the use of nanomaterial for the heat transfer enhancement of coolants and then its use in the different cooling strategies. Further based on the studied reviewed, it is proposed that nanomaterial can be used for the enhancement of BTMS.

Different battery chemistries, geometries and internal components are discussed in Section 2. The thermal issues in them are highlighted and their usefulness is explored for EVs applications. One of the important features of this review study is that along with cooling methods of batteries, this paper also highlights the root causes of the thermal issues in batteries. Section 3 highlights the different battery characteristics such as electrical, chemical, and thermal, and studied the thermal issues from these characteristics. Also, in this section, the effect of different temperatures on batteries, heat generation and heat dissipation modeling is reviewed. Heat generation and heat dissipation modeling is very important for effective development of the BTMS. Section 4 provides information regarding BTMS, its sub-components and why it is important. This section deals with different cooling strategies to solve the thermal issues in batteries. Different studies are reviewed for the thermal performance enhancement in Section 5 by incorporating nanomaterials in liquid and PCM based coolants. The studies pertaining to use of nanomaterials in PCM are reviewed in two sub-sections i.e. addition of different thermal conductive additives and the impregnation of PCMs into different metal foams and carbon foams. Studies pertaining to the incorporation of composite PCM into the battery pack for thermal management are reviewed. Finally based on all the studies reviewed, conclusion has been made regarding the efficacy of use of nanomaterial in BTMS for EV application.

2. Batteries

Batteries are the power storage devices. They supply the power to a load by converting stored chemical energy into electrical energy. Batteries are a crucial component of an electrical device since they are responsible for powering up the whole setup; therefore, they need extra care and maintenance. Stored chemical energy gets converted into electrical energy when an electrochemical oxidation-reduction reaction takes place within the battery [31]. Batteries can be differentiated into four groups as presented in the following subsections.

2.1. Primary cells

This branch of batteries is the one which is single time usable, they can be used only once and it's not possible to charge them again after the discharge. After a single-use, these batteries need to be recycled. These cells are normally used in appliances like T.V. remote, cameras, wall clock, etc.

2.2. Secondary cells

Secondary batteries are normally called as rechargeable batteries. These batteries can be used more than one time and after discharging it can be charged again for their further use. These batteries can be used in places where the physical changing of batteries is not feasible such as mobile batteries, laptop batteries, etc. There are various chemistries available in rechargeable batteries. They have different properties and according to which they are used in different applications, such as for EVs, high energy density batteries are a primary requirement, therefore Li-ion batteries are the best option. Some of the rechargeable batteries are discussed below which have the potential to be used in energy storage applications.

2.2.1. Lead-acid battery

Mainly lead-acid battery technology was used earlier and it is relatively cheaper. It has an energy density in the range of 30 – 40 $WhKg^{-1}$ and a cell voltage of 2V [32]. This battery technology can be used for applications such as the starting of combustion vehicles and backup power supplies such as UPS battery, inverter battery, etc. Also, this can be used in a low range of transportation EVs. For the range of approximately 200 Km, about 500 Kg lead-acid battery cells are required whereas only 150 Kg Li-ion cells are sufficient for this application [33]. The main advantages of lead-acid batteries are low cost (around USD 65-120 per KWh), low self-discharge, and wide allowance of charging-discharging temperature [32]. Lead-acid batteries also have few thermal issues, as sealed lead acid batteries are prone to thermal runaway effect. In the sealed lead-acid batteries, thermal issues are visible during overheating due to the oxygen recombination at a negative electrode which leads to exothermic reactions and an uncontrolled rise in temperature [34]. The possibility of the occurrence of thermal runaway in a lead-acid battery is low as compared to Li-ion batteries [32].

2.2.2. Nickel (Ni) based battery

Recently, this technology proved its existence in hybrid vehicles. Nickel-based batteries are recently used by Toyota in its vehicle, Toyota Prius. Different types of nickel-based batteries are available according to the materials used for electrodes such as Nickel Metal Hydride (NiMH) battery, Nickel Cadmium (NiCd) battery, etc. This battery technology has an energy density in the range 60–80 $WhKg^{-1}$ and a cell voltage of 1.2 V, which is quite low [35]. The main advantage of this type of battery is a low cost, around USD 300–600 per KWh, which is substantially less as compared to Li-ion batteries [36]. However, this technology has several disadvantages that limit its applications such as low energy density, low cell voltage, memory effect, an effect that causes them to hold less charge and hence they require periodic charge and discharge and they require complex recycle procedure [37]. Nickel-based batteries have good performance in an ambient temperature range of 70–90° F [38]. An increase in ambient temperature and charging current increases the thermal issues which can lead to an increase in the chance of thermal runaway. Due to the drawbacks such as low energy density, low cell voltage, memory effects, and thermal issues, it is currently not quite suitable to be used in EVs.

2.2.3. Sodium (Na) ion-based battery

Research on the performance of Na-ion batteries started from the 1930s after the discovery of sodium ion conductive materials [39]. Na-ion battery technology is a good alternative in the field of batteries because it uses more earth-abundant materials for their production. Na-ion batteries perform very similarly to the Li-ion battery, the energy density is in the range of 100-115 $WhKg^{-1}$ and cell voltage around 3.4 V [40]. The installation of Na-ion batteries is less expensive, for the grid-scale applications the cost of Na-ion battery is around USD 445–555 per KWh [41]. However, it has relatively low energy density and low specific power, around 150 WKg^{-1} [42]. Due to their properties, Na-ion batteries can only apply to the stationary energy storage system and short-range vehicles. Regarding the thermal behavior, James et al. [43] show in their study that Na-ion batteries also shows similar thermal runway mechanism as Li-ion batteries.

2.2.4. Lithium (Li) ion-based battery

Li-ion battery technology is the most promising technology for the present and near future. Due to its significant potential in various applications including EVs, most of the researchers studied this technology as compared to others [44,45]. Li-ion batteries have energy density in the range of 80–220 $WhKg^{-1}$ and the cell voltage is in the range of 3.3–3.7 V [46,47]. However, it has a high cost, more than around USD 700 per KWh [48]. It possesses high energy density and longer life as compared to other alternative battery technology. Due to its advantageous characteristics, the applications of the Li-ion batteries are wide. It can be used in laptops, mobile phones, EVs and other portable electronic devices as well. But this technology has some safety issues which need to be addressed using appropriate methods such as by incorporating effective thermal management system. This technology has issues such as thermal problems, high heat generation and also overcharging may lead to fire [49].

This section provides an overview of the different types of rechargeable batteries. In this study, some limited types of rechargeable batteries are discussed which are mostly used or can be the alternative method for the near future. Table 1 provides the detailed properties of different rechargeable batteries and a suitable comparison between them. It can be deduced from Table 1 that Li-ion battery is the most suitable in different applications due to its properties like high energy density, high cell voltage, etc. While other batteries with different chemistries are not still quite feasible to be used in transportation vehicles and portable devices. Therefore, this study considers the Li-ion battery in further discussion.

2.3. Reserve batteries

This type of battery is somewhat different from others. These types of batteries are for the specific and special purpose, as they only get activated when needed. This battery construction is widely used as the power source for the components of artillery projectiles. To avoid the chemical deterioration the battery cells are stored at dry condition and get wetted with the electrolyte when the artillery shells get loaded with the weapon for firing [52]. This application indicates the mechanism of reserve batteries which is the main reason for its long life.

2.4. Fuel cells

Fuel cells do not clearly come under the tree of batteries, some source [31] consider it as battery while others do not [53]. Fuel cells are actually not like other branches of batteries. Fuel cells can be used similar to batteries with the help of some external fuel supply source.

From the study of different types of available batteries and also the different possible battery chemistries in secondary batteries, it can be concluded that the Li-ion battery is the most suitable for this review study. Li-ion batteries have characteristics such as high energy density, considerable life, etc. which makes it more widely applicable as compared to others. The descriptive study of Li-ion battery about its internal components and the widely used geometric configurations are presented in Section 2.5.

2.5. Li-ion battery components and geometric configurations

This study mainly focuses on the secondary or rechargeable cells. In the secondary cells, the Li-ion battery is again the area that needs more study due to their properties, which makes it widely applicable. In this study, Li-ion batteries are chosen since lithium is the lightest metal and it can produce lighter batteries as compared to others. Also, it has a high specific energy and capacity [54]. A typical Li-ion cell is composed of several subcomponents such as- electrodes, positive and negative, separators, electrolytes, collectors, and cases. The most important component in it is an electrode, since this is responsible for the determination of capacity and energy density of the battery. Generally, for negative electrodes, carbonaceous compounds are chosen for example- graphite, mesocarbon microbeads, etc. in which graphite-based carbon is the most popular [55]. For the fabrication of safe battery cells, the high reactivity of lithium creates several challenges in the path which can be overcome

Table 1
Comparison of different rechargeable batteries.

	Lead Acid battery	Nickel based battery	Sodium ion-based battery	Lithium ion-based battery	References
Cell Voltage	2 V	1.2 V	3.4 V	3.3 – 3.7 V	[32,35,40,46,47]
Energy density	30 – 50 $WhKg^{-1}$	60 – 80 $WhKg^{-1}$	100 – 115 $WhKg^{-1}$	80 – 220 $WhKg^{-1}$	[32,35,40,46,47]
Cost	around USD 100 per KWh	around 700 – 800 per KWh	around USD 445 – 555 per KWh	more than around USD 700 per KWh	[32,36,41,48]
Thermal issue	Yes	Yes	Yes	Yes	
Cycles	250 -1000	300 – 50,000	2,500 – 40,000	around 3000	[31,50,51]

by choosing any compounds capable of giving lithium ions [56]. Many studies are going on to sort out this problem and to increase the performance of batteries. In this situation, a silicon-based anode for li-ion batteries will be a better option [57]. But the short ionic and electric conductivity of silicon-based materials can create big dissimilarity which can lead to the reduction in energy storage capacity of electrodes [58,59].

Apart from electrode other components are electrolyte; they are generally dissolved in organic solvents such as ethylene carbonate ($C_3H_4O_3$), ethyl methyl carbonate ($C_4H_8O_3$), etc. [60]. Separators are present in the batteries to prevent touching of positive and negative electrode with each other. It behaves as an electrical insulator; also shuts the cell down during thermal runaway of batteries which makes it a safety switch [61,62]. At last, case is a kind of container or seal that contains all these components together with having promising mechanical and thermal properties.

In the case of electrical vehicles normally two different configurations of batteries are used, namely cylindrical and prismatic. Prismatic can be further categorized into prismatic hard case cells and prismatic pouch cells [63]. In all these three types of geometry, the inner structures, from the electrode to separator are different from one another in terms of dimensions, method of manufacturing, etc.

The selection of batteries in the automotive industry is purely based on specific demand. All types of batteries have their specific property, one is having high energy density while the other has more mechanical strength, etc. It is also true that a single battery is not enough to power the whole vehicle, therefore multiple batteries are required and they should be placed in a container in a specific arrangement with some other hardware components. This complete setup constitutes a battery pack. To develop a thermally balanced battery pack, it is necessary to study the thermal behavior and structural property of all three types of batteries. Such a study will help in deciding which type of battery will be a better option for a specific application.

Each cell geometry has advantages and disadvantages. Cylindrical cells are compact and easy to manufacture, also it is mechanically stable. But as they have a small size, their energy density is low which results in the requirement of a greater number of cells to meet up the large energy size battery pack and this also adds additional cost to the system [65]. Prismatic hard-case type batteries are mechanically robust but due to their complex shape, they are expensive to manufacture. On the other hand, prismatic pouch cells have higher energy density as compared to the two other described geometries [66]. They are lightweight, which makes them user's first choice for EVs battery pack [66]. But prismatic pouch cells have some other issues such as, mechanically weak, prone to swelling, temperature increases rapidly if the adequate thermal management system is not present and also some external casing will be required for holding them [67].

For the development of an effective battery pack, with minimum issues, battery characteristics need to be analyzed after the selection of battery. Section 3 will provide an insight regarding the different characteristics of a battery such as electrical, thermal, and chemical. This insight into the battery characteristics is necessary to solve battery issues and for the development of effective BTMS.

3. Battery characteristics

For the designing of an effective energy storage system, the study of detailed battery characteristics is important. It is important to be well aware of electrical characteristics such as battery voltage, current, capacity, and how it affects battery performance. The thermal and chemical characteristics are also needed to be analyzed before the designing of the proper thermal management system. The review study in this manuscript is mainly concerned with the BTMS; therefore, this section will give the information regarding how different battery characteristics, such as electrical, thermal, and chemical, affect the thermal performance of a battery. For the designing of the thermal management system, knowledge of heat transfer in batteries is important, and hence the heat generation and heat dissipation models are also reviewed in this section.

3.1. Electrical characteristics

Electrical characteristics of Li-ion battery signify how well it is working in the circuit. Electrical performance of the battery depends on charge/discharge, ambient temperature [68], and State of Health (SOH) [69], which can be determined by internal resistance [70], working voltage, and available capacity [71].

Electrochemical parameters of a battery change with its state and operating conditions [72]. On increasing the discharge rate, the operating voltage becomes lower [73]. Reduction in ambient temperature also leads to the working voltage reduction of batteries [74]. An interesting phenomenon happens when the operating temperature is close to 0°C, then the available capacity decreases rapidly while the internal resistance of the battery increases. The battery aging process also has an impact on electrochemical parameters. When the battery cycle increases, the terminal voltage lowers down while internal resistance increases gradually [75].

Internal resistance has a critical role in the thermal behavior of batteries. The internal resistance of the Li-ion batteries can be estimated by 4 methods [76]: Voltage-Current (V-I) characteristics, AC impedance spectroscopy, resistance by the over-potential method and rapidly intermittent charge/discharge method. Heat generation in the batteries is mostly estimated using the internal resistance and over-potential method [77].

As discussed, the State of Charge (SOC), SOH, and ambient temperature affect the internal equivalent resistance of the battery and all these characteristics should be considered during battery state estimation and battery heat generation modeling.

3.2. Thermal characteristics

Performance and behavior of Li-ion batteries are closely related to temperature range and temperature uniformity within the battery pack in EVs. Uneven temperature distribution leads to abnormal charging/discharging rates [78]. The temperature range of the battery pack is based upon the manufacturing process, cell chemistry, and design of battery cells [79]. Electric vehicles are used in different ambient temperature conditions worldwide, both in low temperatures and high-temperature regions. The battery performance is affected by these extreme temperature conditions accordingly. The impact of these extreme conditions results in undesired chemical reactions and structural damages. According to thermal characteristics, effective temperature control is necessary as heat generation in battery cells is due to internal resistance and polarization [80]. Hence optimum temperature is an essential feature of an organized battery management system to maintained charge/discharge.

3.2.1. Effects of temperatures

Possibilities of different ambient temperature conditions available for battery pack are namely low, high, and differential temperature conditions. The impact of these temperatures is not the same on performance, life, and inside the chemistry of batteries. The consequence of low, high, and differential temperature conditions are discussed below. Fig. 1

It is a major concern of EVs manufacturers to design batteries for operating at lower temperature conditions. There are several negative impacts of this abnormal temperature condition on charge acceptance [81], energy and power capacity [82], battery life [83], battery performance [25], and among all these, decreased ionic conductivity inside a battery cell is prominent. Bugga et al. [84] performed laboratory tests on enhanced electrolyte of battery cells and observed a 50% yield at -60°C under moderate discharge rate. Jaguemont et al. [85] observed

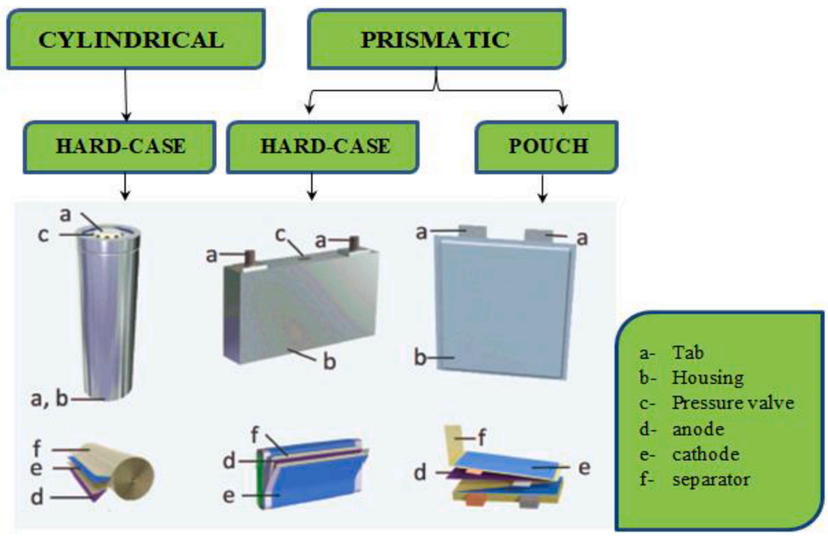

Fig. 1. Different shape configurations of Li-ion batteries [64].

energy delivered, in Wh, for a 100 Ah lithium $LiFePO_4Mn$ HEV battery at different ambient temperatures of 25°C, 0°C, -10°C and -20°C for 50 A, 100 A and 300 A discharging current as depicted in Fig. 2. The general trend shows higher energy delivered at 25°C than other temperature conditions. From Fig. 2, it can also be observed that energy delivered at low and high temperature is nearly same because of the cell heat itself at low temperature under high discharging current. Power loss and safety issues in Li-ion batteries at low temperature are due to the formation of solid electrolyte interface (SEI) and lithium plating respectively [86]. Several researchers have worked on technology to improve the low temperature performance of Li-ion batteries as it is practically impossible to avoid the use of EVs in cold environment condition. Fan et al. [87] worked for -20°C environmental condition by performing computational analysis and external heating considering inlet liquid temperature and mass flow rate, their research suggested that increasing inlet liquid temperature and mass flow rate helped in bringing battery pack at optimum working condition even at low ambient temperature due to external heating. But there is limitation of flow rate to $0.065 kgsec^{-1}$ and inlet liquid temperature of around 45°C for optimum working. Further research work in this direction was performed by Ouyang et al. [88] at low and normal temperature condition (0°C, -20°C) by incorporating insulating material to study losses in battery, their study suggested that high heat is generated in batteries at such low temperature condition due to larger internal resistance inside. Based on the literature surveys it can be concluded that low ambient temperature reduces the performance and the life of Li-ion batteries and heating the battery pack is one way to get optimum performance and maintain long life span of Li-ion batteries.

Main challenge of Li-ion batteries is their operation at elevated ambient temperature. Battery life is significantly degraded at high-temperature conditions. Safety at elevated temperatures is the main concern in the Li-ion battery pack. Apart from the poor performance of the battery pack due to the high ambient temperature, it is also vulnerable to overheating which is caused by excessive heat generation. Heat is generated inside the battery due to electrochemical reactions in the reversible or irreversible process [89]. The uncontrolled heat generation and rapid rise in the cell temperature of the battery pack can lead to the thermal runaway. It is necessary to take precautionary steps to deal with the high ambient temperature conditions. For operating Li-ion batteries at a higher temperature, the solid electrolyte present in the battery should possess high ionic conductivity at operating temperature of about ideally $0.1 Scm^{-1}$ at 400°C and solid electrolyte possess low ionic conductivity at storage temperature range (-40°C to +70°C) to avoid the chance of self-discharge [90]. Another phenomenon

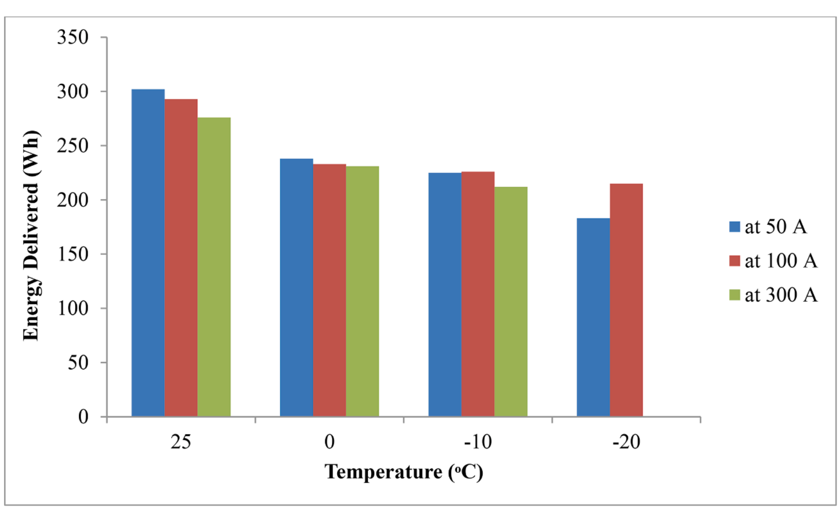

Fig. 2. Energy delivered at low ambient temperatures for different discharging current [85].

associated with batteries at abnormal temperature is battery aging which is caused due to the high temperature and affects the performance and ultimately leads to the reduction of life span [91,92]. When Li-ion batteries made from Ni cathode are operated at a higher temperature, it causes battery capacity decrement and increased impedance. Schipper et al. [93] performed their study and suggested to add the layer of inert compounds like ZrO_2 and performing doping with cations like Zr^{4+}, Al^{3+}, Mg^{2+}, etc. Jiang et al. [94] utilized thermal stability of thermosetting polyimide (PI) nanofibers in the form of soaked polyimide nonwovens separator inside Li-ion batteries for optimum charge/discharge rates, good ionic conductivity (at temperature 120°C) and appreciable oxidative potential (>4.5 V).

Non-uniform temperature distribution of battery cells, battery modules, and battery packs lead to a decline in the performance of batteries. Due to the presence of separator, current collectors, and electrodes, the temperature across different locations in a large battery pack is found to be non-uniform [95]. Several literature surveys mentioned that due to heterogeneity in temperature distribution inside battery cells because of geometric consideration, physical parameters, and different components, the heat generation is not the same across the whole battery pack which leads to the uneven temperature distribution [96]. Robinson et al. [97] studied non-uniform temperature distribution across the whole battery pack consisted of 18650 Li-ion cells, for a discharge rate of more than 0.75 C, it was observed that heating effect was significant at the positive terminal of a cell. Non uniform temperature inside the battery module or battery pack resulted in a serious impact on performance, cell reactions, and life span [26,98]. Kuper et al. [99] discussed in the study of different thermal management strategies for EVs that only about 5°C change in the temperature distribution among cells of a battery pack can cause about a 10% loss in the power capability. Therefore, the temperature distribution among cells, battery modules, and battery pack are also one of the major concerns during the designing of BTMS.

3.3. Thermal runaway

First priority of the user should be battery safety along with personal safety. Long exposure of battery to high temperature leads to battery swelling, non-uniform temperature distribution, which has a direct effect on battery thermal stress and strain. When battery crosses the limit of optimum temperature range, then a series of undesirable exothermic reactions start to occur which causes the rapid increase in battery temperature. This series of reactions and quick temperature rise leads to an incident termed as thermal runaway. During thermal runaway, a series of exothermic reactions take place one after the other [100]. The heat and gas produced during the thermal runaway may lead to the fire and explosion in the battery [101,102]. The reason behind the thermal runaway can be high temperature, overcharging of batteries, short-circuiting, and nail penetration [103].

Battery thermal characteristics are also dependent on the battery states and are affected them. Lithium Ferro-phosphate, LFP, and NCM (composed of Lithium, Nickel, Cobalt, and Manganese) batteries were tested by Wang et al. [104] at different SOC. They concluded that high SOC batteries are more prone to thermal runaway. According to this study, for the fresh batteries if the SOC increases then the temperature at which thermal runaway occur decreases. While aged batteries have no significant impact on the temperature at which thermal runaway occurs when SOC is increased [105].

In the present scenario, there are few technologies available for the prevention of thermal runaway. One solution is the addition of an inhibitor in battery materials [106]. But there is no effective and straight forward method available to prevent the degradation of batteries at high temperature. The best possible method for the prevention of thermal runaway is the development of effective BTMS. BTMS will help in effectively managing the thermal behavior of batteries. Batteries working under safe operating temperatures and uniform temperature distribution in the battery pack slows down the possibility of the spread of thermal runaway [107].

3.4. Chemical characteristics

Li-ion batteries are widely used in different applications like EVs [108], laptop [109], etc. due to their properties like high energy density. Electrochemical reactions occurring between positive and negative electrodes allow the batteries to serve their basic functions [110]. Degradation of electrode materials during electrochemical reactions leads to a decrease in the performance of the battery [111]. Chemical characteristics of a Li-ion battery help to get a better insight of internal reactions that lead to heat generation. Chemical characteristics of any battery play an important role while selecting effective thermal management of battery. Various types of Li-ion cells are used in different applications depending upon their characteristics required in the system. Lithium Nickel Manganese Cobalt Oxide (NMC) cells are one of the more successful and widely used batteries due to their various advantages like continuous discharge current up to 20A. Although they have a low specific power of about 2800mAh [112], but they supply this value of specific power even at moderate loading conditions and for longer cycle life. NMC cells are a good choice for EVs due to various advantages caused by the combination of Nickel and Manganese. Combination of these metals with each other eliminates the drawbacks of each metal and finally contributes to high specific energy and good stability [112].

Lithium Nickel Cobalt Aluminum Oxide (NCA) cells also deliver high specific power, the high specific energy of about 200-260 $Whkg^{-1}$ and long life, like NMC cells. These cells provide greater chemical stability compared to other types of cells. These cells are widely used in electric drive units and medical devices [108,113].

Lithium iron phosphate ($LiFePO_4$) cells are very often used in EVs applications due to their high discharge properties. $LiFePO_4$-graphite batteries have shown fast charging capabilities. These types of batteries can be charged up to 60% of their nominal capacity within 5-minutes using fast charging system [114]. Although these cells have a lower nominal voltage of about 3.2V and specific energy of about 90-120 $Whkg^{-1}$ compared to other cells like NMC and NCA, but they remain less stressed compared to other cells if operated at high voltages for a very long time. $LiFePO_4$ material possesses certain exclusive characteristics like partial solid solution regions, which increased the complexity of modeling of these batteries. Various electrochemical models were used to study the complex mechanisms occurring within these batteries [114]. These cells have high-temperature range of about 270°C for thermal runaway. These cells are well known for their long life of 1000-2000 cycles [112].

Lin et al. [115] Studied the variation of heat generation rate of $LiFePO_4$ and NMC cells with ambient conditions and discharge rates. In the case of $LiFePO_4$, it was observed that when the battery was operated at higher ambient temperature, the heat generation rate remains nearly constant initially and increases exponentially at the end of the discharge process. While on the other hand, the heat generation rate was very high in the beginning when the battery was operated at low-temperature conditions after that heat generation rate decreased for a particular discharging period and increased at the end of discharge. Heat generation rate increases as the discharge current increases. The heat generation rate followed a different trend in NMC batteries compared to $LiFePO_4$ batteries. A significant dependency of SOH on the thermal behavior of NMC batteries is considered as the reason for this variation in the heat generation rate. Heat generation rate curve of NMC cells showed three peaks during the discharging of the battery at high ambient temperature. These peaks disappeared at low ambient temperature conditions. Heat generation rate also increased with an increase in discharge rates as in $LiFePO_4$ batteries.

The reactions involved at the cathode and anode during electrochemical reaction taking $LiMn_2O_4$/graphite as an example is shown below [116]-

Positive Electrode-

$$Li_{y-x}Mn_2O_4 + xLi^+ + xe^- \underset{Charge}{\overset{Discharge}{\longleftrightarrow}} Li_yMn_2O_4$$

Negative Electrode-

$$Li_xC_6 \underset{Charge}{\overset{Dscharge}{\longleftrightarrow}} Li_0C_6 + xLi^+ + xe^-$$

Electrochemical reactions which occur at positive and negative electrodes are exothermic, which leads to the increase in temperature of the cell. As the temperature of the cell increases and goes beyond 75-80°C, it promotes the decay of the solid electrolyte interphase (SEI) layer of anode [117]. Lithium starts to react with the electrolyte solvent, resulting in an exothermic reaction. The electrolyte also starts to break down at 100°C-110°C, resulting in the generation of a large amount of heat and various gases in cells. This process continues with the decay of separator and results in a contact between anode and cathode layer which causes a short circuit in the cell. Therefore, proper thermal management of batteries is required for extreme ambient temperature conditions to have balanced electrochemical reactions inside batteries to maintain safety and long life.

3.5. Heat generation and heat dissipation modeling

For designing an effective thermal management system, accurate knowledge of the amount of heat generation inside the batteries is important. The rate of heat generation in batteries is different in different conditions such as the heat generation during charging is less as compared to heat generation during discharging but still, batteries are more prone to thermal failure during charging due to the rapid temperature rise and non-uniform heat generation [118]. Various battery heat generation models like internal resistance model, electrochemical thermal coupled, and electrical thermal models are used depending upon the type of approach used [119]. Heat is generated inside the battery due to ohmic losses and reversible entropy change during electrochemical reactions [120]. These models are used to get a better insight of the physical mechanism of battery behaviors to predict the heat generation and temperature distribution of a battery pack. For the estimation of temperature distribution and heat generation in the batteries, the Thermal resistance model is the simplest one and it is used widely by researchers [121]. Electrochemical model gives information about the internal temperature distribution and heat generation within the battery pack with the help of electrochemical reactions taking place within the cell by solving non-linear differential equations. Although this model gives very accurate results this model needs high computing systems to solve non-linear equations [122,123].

Electrical equivalent circuit model (ECM) is widely used to estimate SOC and other battery parameters as it eliminates the complexity of the electrochemical mechanism of battery. This model consists of different types of models like impedance-based, internal resistance, Thevenin-based models, etc. depending upon components like capacitors, resistors, etc. in the circuit [124]. Gu et al. [125] used an electrochemical-thermal coupled approach to find out the heat generation in the battery. Various factors like electrode reactions, joule heating in the electrolyte phase, and solid active materials were considered to determine the heat generated from the battery as shown in Eq. (5) in Table 2. The lumped thermal model was used to predict the temperature distribution within the battery pack as shown by Eq. (6). Sato [126] studied the thermal behavior of Li-ion cells and developed heat generation equations. For the discharging and charging cycle, different thermal behavior factors like reaction heat value, polarization heat value, and joule heating of electric components were studied to find out the heat generation in different cycles. Fathabadi and Bernardi et al. [18, 127] made an energy balance for the battery system by considering battery as a composite material. Furthermore, heat generation equations were also developed by taking electrochemical reactions, phase changes, and mixing process into consideration. Heat generation equations derived from these analyses are defined in a simpler form by Eq. (3) shown in Table 2. Kameyama et al. [128] also considered factors like ohmic loss and entropy change for heat generation within the battery. First-term shown in Eq. (4) in Table 2 indicates the heat generation due to the internal resistance of the battery, while the second term shows the effect of entropy change on net heat generation from the battery pack.

Table 2
Heat generation models.

S. No	References	Equations used
1	Sato [126]	$Q_{charge} = -3.37 \times 10^{-2} Q_1 I_c + 3.6R_{t,c}\, {I_c}^2$ **(1)** $Q_{discharge} = -3.37 \times 10^{-2} Q_1 I_d + 3.6R_{t,d}\, {I_d}^2$ **(2)** Q_1–heat generated ($kJmol^{-1}$) I_c, I_d– battery charge/discharge current $R_{t,c}$, $R_{t,d}$– total electrical resistance during charging/discharging
2.	Bernardi et al.[127], Fathabadi [18]	$\mathbf{q} = \mathbf{I}(\mathbf{U_{OC}} - \mathbf{V}) - \mathbf{I}\left(\mathbf{T}\frac{\mathbf{dU_{OC}}}{\mathbf{dT}}\right)$ (3) where Iis discharging current density $U_{OC}$is Open circuit potential Vis the Cell voltage $I(U_{OC} - V)$is Joule heating $I\left(T\frac{dU_{OC}}{dT}\right)$is Entropy change
3.	Kameyama et al. [128]	$\mathbf{q} = \mathbf{r_i i^2} - \mathbf{T\Delta S}\frac{\mathbf{i}}{\mathbf{nF}}$ (4) where qis internal heat generation per unit volume $r_i$is internal equivalent resistance per unit volume iis discharge current per unit volume
4	Gu and Wang [125]	$q = \left\{a_{sj} i_{nj}(\varnothing_s - \varnothing_e - Uj) + a_{sj} i_{nj}\left(T\frac{\partial Uj}{\partial T}\right)\right\} + \sigma^{eff}\nabla\varnothing_s.\nabla\varnothing_s + \{k^{eff}\nabla\varnothing_e.\nabla\varnothing_e + {k_D}^{eff}\nabla \ln c_e.\nabla\varnothing_e\}$ **(5)** where q is heat generation rate the first term on RHS is heat due to electrode reactions the second term is joule heating in the solid active material the third term is joule heating in the electrolyte phase $\frac{\partial(\boldsymbol{\rho}\mathbf{C_p T})}{\partial \mathbf{t}} = \nabla.(\mathbf{k}\nabla\mathbf{T}) + \mathbf{q}$(6) where, ρ is density of the battery Cp is heat capacity of battery k is thermal conductivity of battery q is heat generation rate

Heat dissipation in any process occurs due to conduction, convection, or radiation process. Any particular type of heat transfer process occurring within a body depends on various factors like shape, size of body, environment conditions, and some thermo-physical properties like thermal conductivity, etc. There is no fixed heat dissipation model, used to calculate the heat generation from Li-ion batteries. Selection of heat dissipation model depends upon the types of cooling strategies to be used, the outer casing of battery pack, and the ambient temperature conditions. Heat transfer from a Li-ion cell doesn't take place symmetrically in all directions. Faces, which are closer to the center of the cell, have more heat transfer rate as compared to other faces. In cylindrical cells, heat dissipation in the radial direction is more in comparison to its longitudinal direction. Similarly, in the pouch and prismatic cells, the heat dissipation rate is different in all three directions due to their different length parameters [129].

Properties like thermal conductivity of cells don't follow isotropic nature [130]. Therefore, larger heat dissipation occurs in a direction in which there is a larger value of thermal conductivity. Heat dissipation also depends upon the surface area of the body; more heat will be dissipated from the surface with a larger area. External environmental conditions and thermal properties of coolant also play an important role in effective heat dissipation. Extreme ambient conditions don't allow effective heat transfer from the battery, which limits the effective cooling of the battery. Apart from ambient conditions, type of coolant and its properties like convective and conductive resistance also plays an important role in effective heat transfer.

Heat generation equations have a significant role in developing an effective thermal management system. It is evident from the previous studies that the equations used by Fathabadi et al. [18], Bernardi et al. [127], and Kameyama et al. [128] are commonly used to find out the heat generation in small Li-ion batteries. These equations take ohmic losses and entropy changes into consideration to derive the heat generation equations by neglecting mixing and phase change within the battery. But in the case of large batteries, different factors like joule heating in the electrolyte phase, and solid active materials heat, play an important role in deriving heat generation equations. Furthermore, heat dissipation modeling also has great significance in the development of an effective thermal management system. Since, only through this modeling, the accurate dissipation of generated heat in the battery from the system will be possible. Various factors like ambient environmental conditions and thermophysical properties of batteries affect heat dissipation from a battery. It becomes important to select a better cooling method for effective heat dissipation from batteries.

4. Battery thermal management system

BTMS is a method or approach which combines different software, hardware & miscellaneous components to make the batteries of the battery pack thermally stable. BTMS is a very crucial and important integral part of BMS (Battery Management System) [114,131,132]. The primary goal of BTMS is to maintain the temperature of batteries in the optimal working range [133–135] and to maintain the temperature uniformity in the battery module [136–138]. BTMS plays a very vital role in increasing the lifespan of batteries and in maintaining the thermal safety [139,140]. The usage of batteries is not limited to a particular application and location. It can be used at different locations or preferably at different ambient conditions; therefore, BTMS should be made in a way that it can adjust according to operating or ambient conditions. Ambient conditions where the ambient temperature is below 0°C, it will lead in the degradation of LIBs performance [25,141]. In low ambient temperature applications, there should be some arrangement to increase that temperature, in the same way some method should be present in the hotter climate so that the battery operates at its optimal temperature range. Without proper designing, the usage of these heating and cooling methods may lead to the origin of non-uniformity and variation in the temperature distribution in the battery pack. This can increase the chances of losing thermal stability and safety, and also leads to some problems like lowering the battery life, thermal runaway, etc. [138,142]. Therefore, there is a need to find some methods through which these problems can be solved. Development of an effective Battery Thermal Management System (BTMS) is the only solution for these problems, also it will be helpful in uniform temperature distribution within the battery pack [143,144]. The process that needs to be followed for the development of BTMS is shown in Fig. 3. For the automotive application of Li-ion Battery pack, a good BTMS design must ensure that the overall battery pack would have low weight, compact, able to give reliable output, high feasibility and cost-effective, etc. [145–147]. Thermal management of the Li-ion battery pack can be performed by three methods. These cooling strategies are based on air, liquid, and phase change materials (PCM) coolants. In the following sub-sections, each method is articulated from novice developments to the latest trends in the field and scope of future possibilities.

4.1. Air cooling

Air coolant based cooling strategy is widely used in Toyota Prius, Nissan Leaf, BYD E6, and in some other variants of EVs because of the associated merits such as lightweight and affordable price [27]. Besides the above attributes, researchers like Nelson et al. [148] mentioned the ineffectiveness of air coolant in reducing the temperature of the battery pack to 52°C while the temperature of the battery pack was 66°C when no thermal management system incorporated. There are certain challenges in the implementation of an air-based cooling system due to which effective cooling is not possible, such as, low thermal conductivity and the inadequate designing of the cooling system [149]. It is concluded from these studies that the design of set up and airflow distribution influenced the cooling performance. Hence, efforts have been made for the enhancement of airflow distribution and whole system designing. Pesaran et al. [150] showed the uniformity of battery temperature by proper air circulation with the help of considering a novel air manifold for forced inlet air. Extensive efforts were continued by Heesung Park [151] by performing investigation on improving the passage of forced air without changing the design of the system and found that by considering tapered manifolds and pressure relief ventilation, desired cooling can be achieved. Li et al. [152] did a comparative study based on experimental and CFD analysis on Li-ion ($LiMn_2O_4$/C) battery cell to find out the effect of inlet air velocity. Both experimental and numerical results showed that at an inlet air velocity of 5 ms^{-1}, about 1.5°C temperature rise of the battery pack was observed as compared to temperature rise of about 5°C for natural convection case.

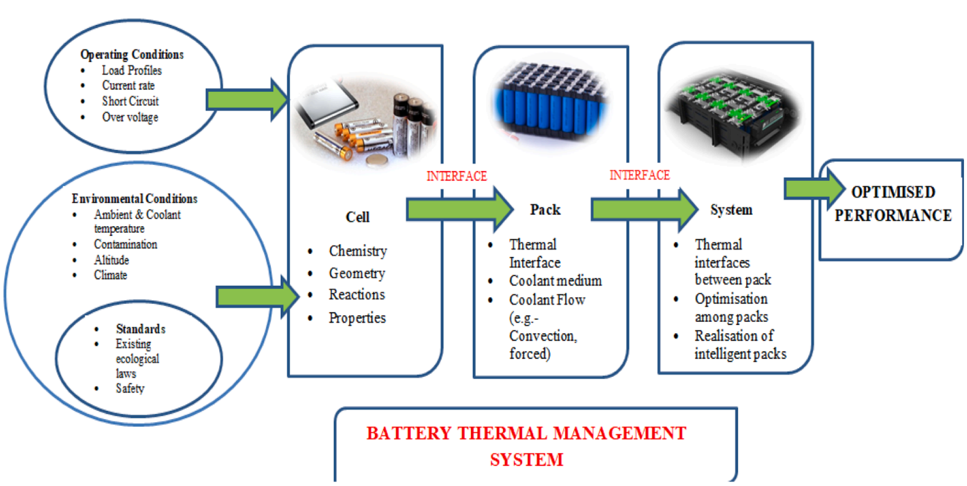

Fig. 3. Flow diagram highlighting the approach for thermal management of battery pack.

This indicates the effectiveness of forced air cooling compared to natural convection. BTMS studies were performed at the battery level by Fan et al. [153]. They conducted a comparative analysis of the effect of cell spacing and mass flow rate on overall temperature uniformity within the battery pack. Their study demonstrated that when cell spacing increases, keeping constant mass flow rate of air, the overall temperature uniformity was improved and the results further showed that when the mass flow rate of fan increases, keeping cell gap spacing constant, then the overall temperature uniformity decreases in the system. Battery's orientation inside the battery pack is also an important focus point. The research was conducted by Wang et al. [17] considering different cell arrangements (1×24 linear, 3×8 rectangular, 5×5 square, 28 cell circular, and 19 cells hexagonal) and the impact of cell's orientation was studied by analyzing temperature distribution within a battery pack with or without forced air. For this study, a 3C discharge rate was considered and the fan was positioned at the top of the battery pack in each arrangement. For every arrangement, forced air cooling effectively reduced the temperature of the battery module in comparison to the case of no fan attached to the system. Apart from cell orientation, length and cross-section area of the cooling path, inlet temperature of coolant air, and mass flow rate influence the cooling performance of the air-based BTMS. From literature review presented in this section [17,154–157], it can be concluded that the cooling performance of the battery module depends upon the arrangement of battery cells within the system and this arrangement can be a series, parallel or series-parallel matrix. In the following paragraphs, an analysis will be done to find out the impact of each arrangement properly, and work done by different researchers will be reviewed.

Series arrangement of battery cells was studied by considering three different possibilities as shown in Fig. 4. For a simple channel shown in Fig. 4(a) [17,154] it was observed that temperature from inlet to outlet gradually increases in the airflow direction due to continuous heat absorbed by coolant in the channel. Limitations of the simple channel were reduced by considering the wedge channel, as shown in Fig. 4 (b) [155], in which area uniformly decreases from inlet to outlet. This led to a gradual increase in airflow rate from inlet to outlet and it resulted in improved surface heat transfer coefficient. It was seen from the results that the implementation of the wedge channel led to a low-temperature difference between inlet and outlet in comparison to the previous series arrangement case. Fan He et al. [155] proposed an improved air cooling strategy in which a simple channel with a reciprocating cooling process was employed, as shown in Fig. 4(c). In this case, two fans were placed at inlet and outlet of the simple channel, and both fans were operated alternatively to produce reciprocating airflow. This strategy resulted in the decrement of parasitic power by 84% and temperature distribution was such that it first increased up to the middle of the channel and then decreased towards the outlet.

Pesaran et al. [147] worked on the effect of airflow direction and concluded that parallel cooling by equally dividing inlet flow to different battery modules resulted in more even temperature distribution compared to series cooling where the air is supplied to all cells using only one entrance. Parallel cooling arrangement results in a more uniform temperature of battery pack cells as the inlet air is distributed equally among battery modules in U and Z parallel configuration as shown in Fig 5 [156] but the designing of these configurations are difficult.

Limitation of both series and parallel configuration led to a better alternative of hybrid series and parallel configuration, combining the merits of both configurations. Three cell arrangements are shown in Fig 6 [157]. These series-parallel combination configurations are arranged in aligned, staggered, and trapezoid cell configuration. Aligned and staggered arrangement noted more temperature rise of the battery pack at outlet due to successive heat transfer by air coolant while passing through different cells in these configurations. But due to decreased area at the exit in the trapezoidal arrangement, this configuration had a lesser temperature at the outlet as compared to the other two cases.

Air cooling is not adequate for high ambient temperature and rapid discharge rate conditions for batteries. From the various numerical simulation and experimental studies, it was concluded that active forced cooling is necessary for these harsh conditions and a passive PCM based cooling strategy can achieve the desired result without any additional power supply [158]. Kim et al. [159] presented in the study that for high energy density batteries (Li-ion batteries) it is necessary to incorporate active cooling while for low energy density batteries (lead-acid batteries) passive cooling can be sufficient. Another limitation of air-based BTMS is that at a higher discharge rate this cooling strategy will not provide the desired temperature drop, hence it will be needed to incorporate other subsidiary cooling strategies in the system [28]. Giuliano et al. [19] studied the improvement in air-based cooling strategy by incorporating open-cell aluminum foam to enhance the overall thermal performance by maintaining batteries temperature under the optimum limit on different charging and discharging rates. Table 3 enumerates the different thermal management systems which used air cooling strategy. Air cooling is prevalent in some situations because of its attributes like cost-effective, less weight, and less complex thermal solutions. Despite unmatched attributes of air cooling such as having low space utilization, recyclable air as the coolant and long service life of the system, this technology still needs adequate exploration for improvement to provide optimum cooling performance at high ambient conditions. There is the need for the exploration of some technique through which the cooling efficiency of this strategy can be improved. Researchers can explore the option of addition of some additives in air which can improve the cooling by sticking on the surfaces of the heated body. The designing of improved cooling system is required which will be able to cool the whole setup by consuming minimum power.

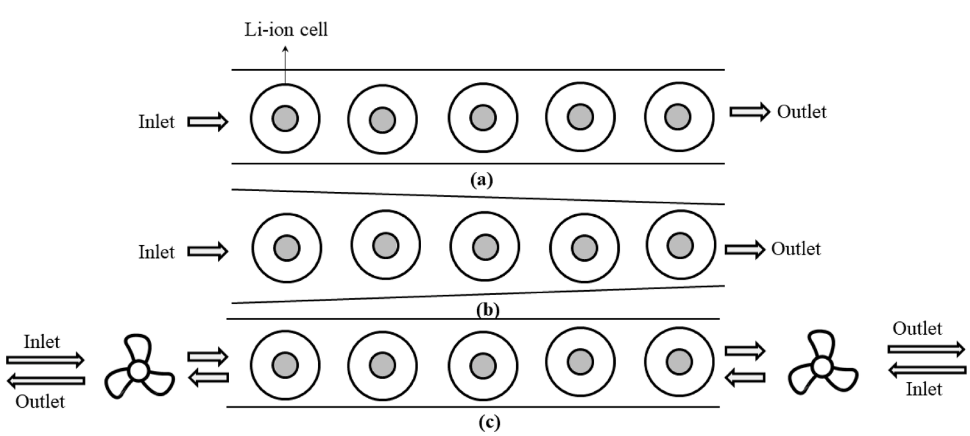

Fig. 4. Series cooling arrangement (a) Simple channel [17,154] (b) Wedge channel [155] (c) Simple channel with reciprocating cooling [155].

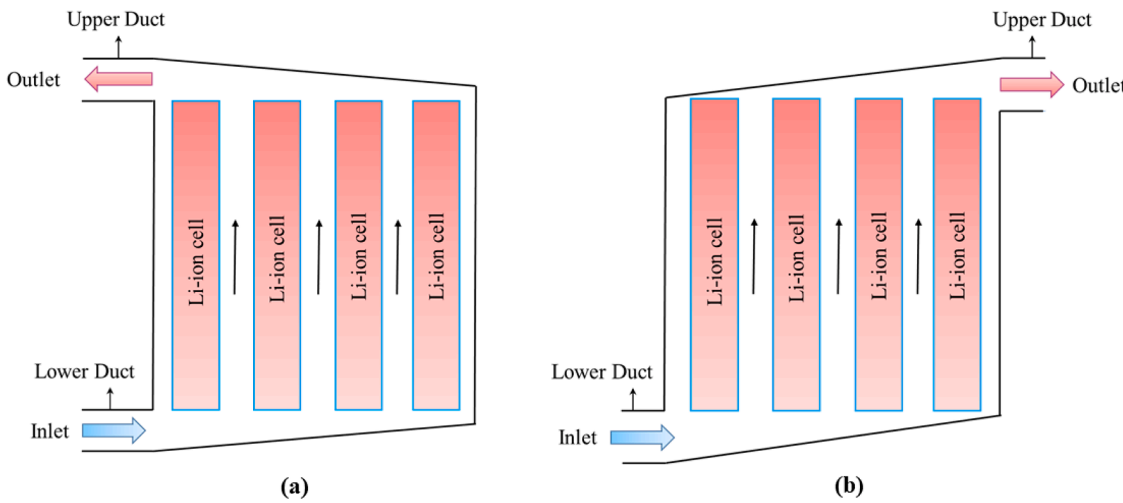

Fig. 5. Parallel cooling arrangement [156] (a) U- parallel arrangement (b) Z- parallel arrangement.

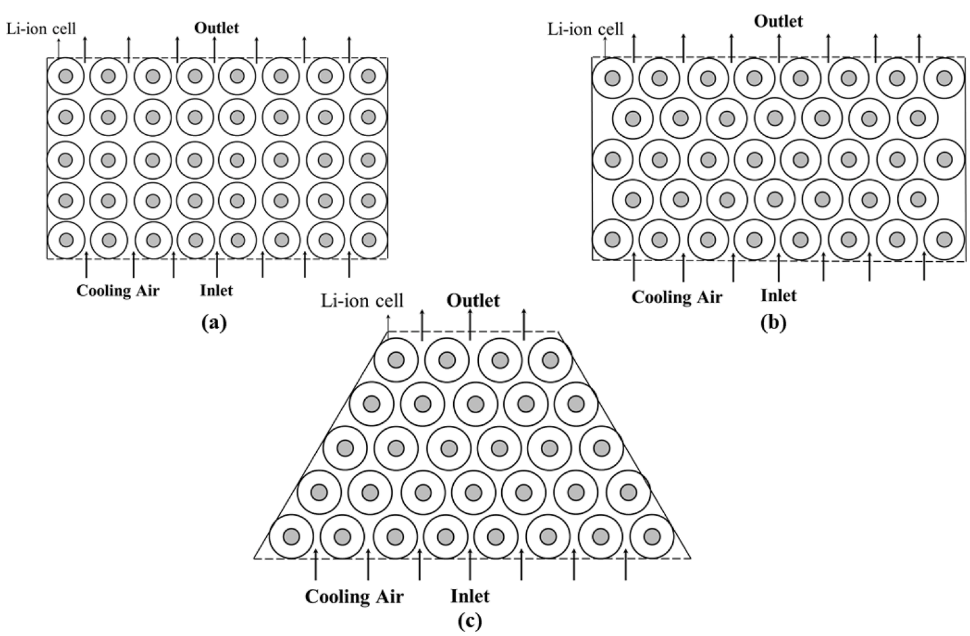

Fig. 6. Series-Parallel mixed cooling arrangement [157] (a) Aligned (b) Staggered (c) Trapezoid arrangement.

4.2. Liquid cooling

Due to relatively higher thermal conductivity and heat capacity, liquid cooling is considered a potential cooling strategy for battery modules. Liquid coolant (e.g. water or water-glycol mixture) is preferred over air coolant under high charging/discharging rates and elevated ambient temperature conditions due to less power consumption and effective management of temperature [148,160]. Fig. 7 shows the schematic diagram with different components of a liquid cooling system. Roger Schmidt [161] in his study proposed that liquid cooling is better than air cooling strategy by a factor of 3500; it also makes systems efficient by reducing 40% parasitic power. Liquid cooling can be classified in two different ways: direct cooling [162,163] in which the battery pack is wholly immersed in circulated dielectric and second is indirect cooling [164,165] in which fluid will not be in direct contact of battery cells but the liquid coolant will flow through tubes/cold plates/jacket attached at the surface of battery cells or battery modules. Chen et al. [166] proposed that indirect cooling is a more viable option for EVs cooling in comparison to forced air cooling, fin cooling, and direct cooling; therefore, more efforts have been put on indirect cooling strategy for BTMS.

Table 4 enumerates the work of several authors related to liquid cooling. Rao et al. [167] investigated the optimum design of the liquid cooling system by reducing pump work, weight, and enhancing cooling performance using computational modeling. The use of cooling plate with different flow passages in liquid cooling system was also studied. The flow path in cooling plate can be serpentine type, U-turn type or multi-channel and so on as shown in Fig. 8. Jarett et al. [168] studied the effect of serpentine flow geometry in the cooling of battery. In this study CFD analysis was used for the optimization of coolant channel and associated factors like pressure drop, temperature uniformity and average temperature. Results showed that on increasing the width of the serpentine channel, the pressure drop and average temperature can be reduced. It was noticed that best design of flow channel for better temperature uniformity requires that the cross section of channel increases gradually with the flow direction. Panchal et al. [169] considered a cooling strategy with a U-turn cooling plate and performed a CFD analysis by considering only a single battery. The study suggested that

Table 3
Different research works showing air based cooling system.

S. No.	Reference	Analysis method	Cell type	Battery pack configuration	Results
1.	Wang et al. [17]	CFD analysis	• Sanyo 18650 Li-ion cylindrical battery with 1.5Ah nominal capacity and 3.7V nominal voltage	• 5 different cell arrangements were studied. • 1 × 24 linear, 3 × 8 rectangular, 5 × 5 square, 28 cell circular and 19 cells hexagonal arrangement.	• 3C discharge rate was considered and fan was positioned at the top. • Forced air cooling was better than the case when no fan was attached to the system.
2.	Giuliano et al. [19]	Experimental analysis	• 50Ah Lithium titanate cells	–	• Incorporated passive cooling using aluminium foam with the air cooling strategy. • Thermal performance was increased after the addition of passive cooling method with active cooling.
3.	Pesaran et al. [147]	Analysis using MATLAB models and CFD from ANSYS Fluent	• Lead acid battery with nominal capacity and voltage as 16.5 Ah and 12V respectively.	• Battery module with 4 battery cells	Reduction in temperature of battery temperature uniformity in battery pack increases for parallel cooling technique.
4.	Pesaran et al. [150]	Computational analysis and experimental testing	• Lead acid battery with nominal capacity and voltage as 16.5Ah and 12V respectively	• HEV battery pack with 30 cells	• To maintain the temperature uniformity in battery pack, air circulation was done using air manifold for forced inlet air. • It was seen that more power were needed in case of FUDS 1.3 cycling for the proper thermal management.
5.	Park et al. [151]	Computational analysis using Star CCM+ software	• Cell considered for analysis was having the density, specific heat and thermal conductivity as 2700 Kgm^{-3}, 900 $JKg^{-1}K^{-1}$, and 240 $Wm^{-1}K^{-1}$ respectively.	• HEV battery pack with 72 cells in two rows to operate 270V and 1400Wh	• Five different layout of air cooling system were analyzed. • In the type V cells arrangement, the cooling was enhanced by considering tapered manifold and pressure relief ventilation.
6.	Li et al. [152]	Wind tunnel testing and CFD simulation using ANSYS Fluent	• A123 26650 Li-ion battery with nominal capacity and voltage as 2.3Ah and 3.3V respectively.	• Battery module with 2P4S configuration with the rating as 4.6Ah and 12.8V	• Forced air cooling reduced the maximum temperature reached
7.	Fan et al. [153]	CFD analysis using ANSYS Fluent	• Prismatic cell with 15Ah nominal capacity	• Battery module consisted of 8 cells	• Cell spacing of 3mm was found to be the best choice. • Temperature uniformity increases with increase in cell spacing for constant mass flow rate. • For the constant cell spacing, as the mass flow rate of coolant increases, temperature uniformity decreases.
8.	Wang et al. [154]	Experimental analysis using wind tunnel and numerical analysis using CFD models	• A123 26650 cylindrical Li-ion cells with nominal capacity and voltage as 2.5Ah and 3.3V respectively.	• Battery module consisted of 4 cells were used for study	• Controller based cooling technique was developed. • Parasitic power was reduced up to 30% by using the controller based cooling strategy.
9.	Sun et al. [156]	Wind tunnel testing and CFD analysis	• A123 26650 cylindrical Li-ion cells with nominal capacity as 2.5Ah.	• Battery module with 4 cells.	• Simple channel with reciprocating cooling process were employed. • Parasitic power was reduced by 84% and temperature uniformity was increased.
10.	Yang et al. [157]	Computational analysis using COMSOL Multiphysics	• 26650 $LiFePO_4$ battery cell was used for study	• Battery module with 6 × 10 cells in staggered and aligned cells	• Temperature rises of cells were lowered in aligned cell structure as compare to the staggered cell arrangement. • Temperature uniformity was also better in aligned cell structure.

the temperature of the cold plate was found elevated when operating temperature and charge/discharge rates were high. Huo et al. [170] showed that the effect of flow direction on the performance of BTMS was not significant as the mass flow rate increased. Results showed that on increasing the number of cooling channels the maximum temperature of the battery reduced. The best cooling performance was achieved when coolant was directed to the channel from electrode side. Basu et al. [171] studied liquid cooling, involving flow channel with aluminum conduction element, and introduced the novel concept of thermal coefficient. Using this concept, the system was developed in predicting the temperature of all cells within the battery module, only by knowing the temperature of a single cell. Yang et al. [172] performed the study through finite element analysis considering the liquid metal-based cooling system. It was suggested that under the same flow conditions, more uniform and less temperature was obtained in case of metal-liquid combination as compared to the pure liquid coolant. Wang et al. [173] for the very first time introduced the concept of thermal silica made cooling plates with embedded cooling plates in it. It was observed that as the number of thermal silica made cooling plates and liquid channels increases, the rise in temperature of batteries decreases. In this study four different cases were studied with 1-channel, 3-channel, 5-channel, and 7-channel as shown in Fig. 9. Results showed that both 5-channel and 7-channel system were able to keep the battery within optimum temperature range as maximum temperature reached for 5-channel and 7-channel designs were 39.1°C, and 36.5°C respectively.

Liquid cooling method is considered as a better thermal management option compared to an air-based cooling system due to its several characteristics like high specific heat, thermal conductivity, and high

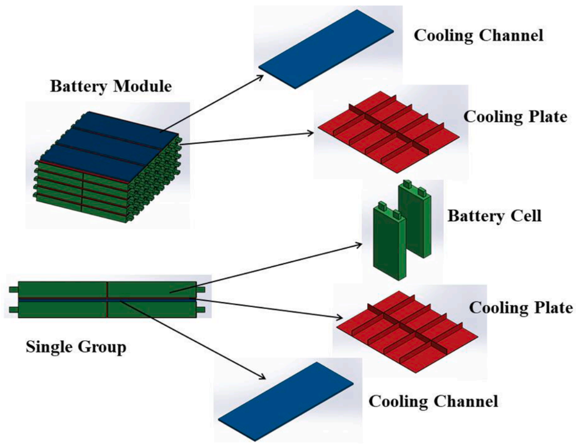

Fig. 7. Schematic representation of liquid cooling system [175].

heat transfer coefficient [174]. Irrespective of these characteristics, the liquid cooling method has several disadvantages due to the complexity in their system design, the addition of extra weight such as a pump for the flow of coolant, high maintenance and initial setup cost. Liquid cooling system also has severe safety issues such as leakage of coolant which may develop serious accidental situations such as short-circuiting of the whole system. These limitations of the liquid cooling system demand the exploration of some technique through which these safety issues can be solved. Some novel systems needs to designed such as liquid cooling through micro channels, mixing of some additive in liquid coolant, etc. which can improve the efficiency and reduce the safety issues associated with the liquid cooling system. Some innovative designs of liquid cooling system have already been used by different automotive manufacturers such as Tesla, Chevy Volt, Ford, BMW i-3 and i-8. The descriptions of their design are not available for the public users due to their privacy policy. Researchers can focus the study in liquid cooling system to reduce its safety issue and new methods of its application.

4.3. PCM based cooling

The drawbacks of liquid cooling strategy shown in Section 4.2 suggest the requirement of a new cooling strategy which can overcome these limitations. PCM based cooling is an alternative to the liquid cooling systems as PCM has a large value of latent energy storing capacity. These properties of PCM allow them to absorb more energy without any temperature rise during phase change [30]. PCM has wide applications such as building applications [176], in electronic components [177], in EVs [178], and thermal management of photovoltaic cells [179]. Selection criterion of a suitable PCM depends upon several

Table 4
Different liquid cooled based BTMS configuration.

Liquid flow system	Novelty of work	Analysis method	Battery type	Coolant material	Charging/ Discharging rate(C rate)	Number of batteries used in analysis	Result of study	Reference
Surface area variation	with the change in surface area heat transfer varies	CFD analysis using ANSYS software	3 Ampere hour capacity batteries	Water	3	6	cooling performance, pump power consumption, and system weight for optimized design	[167]
Serpentine flow path cooling plate	Developed the strategy for the optimization of flow channels	CFD analysis using ANSYS fluent	Rectangular shaped battery	Water-glycol mixture	_	1	Temperature uniformity increases, pressure drop and average temperature decreases	[168]
U-turn flow path cooling plate	• Comprehensive investigation and simulation is conducted • k-ε model is used to simulate water flow in U-turn channel	CFD analysis using ANSYS Fluent	Large-sized prismatic battery ($LiFePO_4$ 20.0 Ah)	Water	1 and 2	1	the temperature of the cold plate elevated by an increase in discharge rates and operating temperature	[169]
Multi-channel flow path cooling plate	Analyzed the effect of increase of channel and the effect of flow direction	CFD analysis using ANSYS FLUENT	Li-ion battery with 700mAh capacity	Water	5	1	Best cooling performance was achieved at system with 6-channel, maximum temperature achieved was 58.4°C	[170]
Flow channels with aluminium conduction element	• novel battery pack design • developed a novel concept of thermal coefficient and demonstrated its efficacy	Star CCM	Li-NCA/C 18650 (17.3 Ah)	Water (aluminium conduction element)	0.6, 0.9, 1.8 and 2.7	30	prediction of all individual cells within the battery module by knowing the temperature of one cell, help in reducing sensor requirement in system	[171]
Using liquid metal	First to use liquid metal as the coolant in battery thermal management	Finite element methods using Fluent 6.3	Prismatic battery ($LiFePO_4$, 100Ah)	Gallium (properties found in 56-58)	1, 2, 3 and 4	4	with the use of the liquid metal cooling system under same flow conditions as that of water cooling, uniform & less battery temperature can be obtained	[172]
Thermal silica plate	First to use thermal silica made plates as cold plates with embedded copper pipes	COMSOL	Prismatic battery ($LiFePO_4$, 20 Ah)	Water	Charged and discharged at different rates	1	As the thermal silica plates and liquid channels increases they result in a decrease in maximum temperature value of the system	[173]

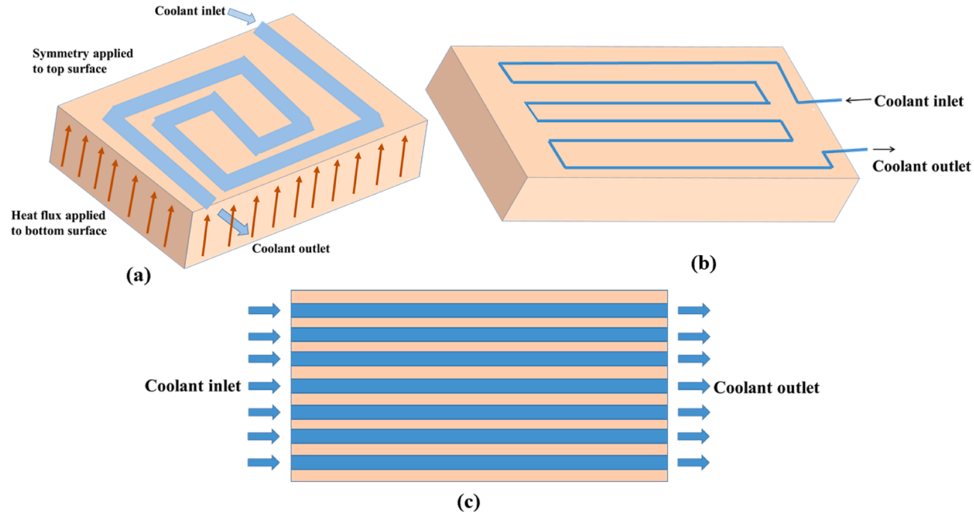

Fig. 8. Different types of flow path in cooling plate (a) Serpentine type [168] (b) U-type [169] (c) Multi-channel type [170].

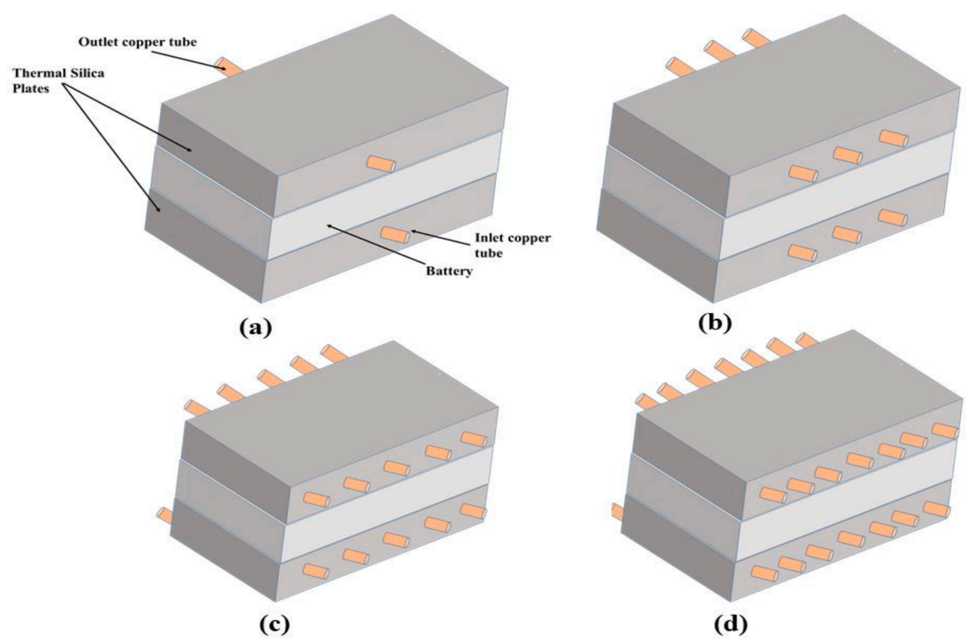

Fig. 9. Schematic representation of different cooling channel in liquid cooling system using thermal silica plate [173] (a) 1-channel (b) 3-channel (c) 5-channel (d) 7-channel.

factors, such as thermal conductivity, heat-storing capacity, operating temperature range, etc. Main characteristics of a PCM, required for effective thermal management of Li-ion batteries are high value of thermal conductivity, stable and non-explosive nature, non-flammable, easily available at a low cost and low volume expansion during melting [28,30,180]. PCM based cooling is also favorable to use in relieving the battery deterioration during long term cycles as studied by Youfu et al. [181] In this study, apart from the obvious decrease in battery temperature from 51.7 to 47.5°C, the cycle life was also increased to 65.3% as compared with the battery module without PCM.

PCM based cooling systems are widely used in battery packs alongwith different types of subsidiary systems to improve the thermal performance of the battery pack. Cicconi et al. [182] studied the use of passive PCM and air cooling system for enhancing the thermal performance of BTMS. The results showed that the temperature of the batteries can be reduced upto 40% combining PCM and air cooling. Fig. 10 presents the schematic diagram of the design used in this study combining air cooling and PCM-based cooling. Many researchers studied the effect of heat pipe assisted PCM based cooling system. Huang et al. [183] investigated the effect of heat pipe on the thermal performance of PCM used in the battery pack. Different types of cooling arrangement i.e. pure PCM, heat pipe coupled with air as a medium, and heat pipe coupled with liquid as a medium were used to study their effect on the thermal performance of the battery. Furthermore, temperature variation and heat-dissipating performance of the battery pack was also studied at various discharge rates. Heat pipe coupled with liquid gave more temperature drop as compared to the other two systems. Zhang et al. [184] studied the impact of heat pipe assisted systems on the thermal performance of PCM based thermal management systems. A battery pack consisting of 18 $LiFePO_4$ cells arranged in 6S x 3P configuration was used for the study. Heat pipes were sandwiched between every two cells to ensure effective heat transfer from cells. The maximum temperature of the battery pack decreased by 1.1°C, 1.9°C, 2.6°C, and 4°C respectively at 1C, 3C, 4C and 5C discharge rates with the use of a heat pipe

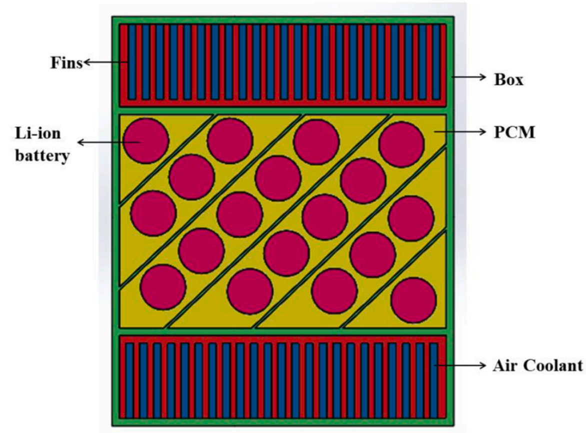

Fig. 10. Schematic diagram of PCM-based cooling with active air cooling [182]
In Table 6, the works of Yang et al. [190] and other researchers are summarized by considering both direct and indirect liquid cooling methods, forced air, and PCM based cooling strategy. It can be interpreted that among all the strategies the simplest, cost-effective, easy to maintain, and integrate is air cooling, but it is not effective. Keeping all factors under consideration, liquid cooling prevails over all other options due to long life, one-time cost-effective investment, and higher thermal performance.

assisted system. Jiang et al. [185] studied thermal management of tube shell-based battery pack using PCM based composite. Forced air cooling was also incorporated in the system for the solidification of PCM. Baffles were added to Aluminum tubes to improve the heat transfer from the battery module. A 3-D numerical model was developed to study the thermal characteristics of the tube shell battery pack. Thermal characteristics of the battery module were compared with the commercially available PCM composite based battery pack of All Cell Technology. Specifications of battery module used for different studies are summarized in Table 5. The addition of PCM composite with tube shell battery module significantly reduces the maximum temperature of the module compared to the case where no PCM was used. The surface temperature of batteries was controlled within the melting range of PCM i.e. 41-44°C and the maximum temperature difference across the battery module always remained below 2°C. Wang et al. [186] investigated the effect of the oscillating heat pipe (OHP) on the thermal performance of PCM based battery thermal management systems. Thermal characteristics of different OHP based thermal management were compared in this study. Concept of battery surrogate was used instead of real batteries due to safety reasons. It was evident from the results that the PCM/OHP based system was more effective as compared to OHP based system in thermal management of battery. Heating time required to heat battery surrogate to a targeted temperature i.e. 50°C was 68.36%, 81.33%, 57.92%, and 37.01% more in OHP based BTM system as compared to PCM/OHP based BTM system at an input power of 20W, 25W, 30W and 35W respectively. Zhang et al. [187] numerically studied the flow and heat transfer characteristics of different open-cell metal foam models. Methods like Face centered cubic (FCC) and Body centered cubic (BCC) were used to develop 3-dimensional metal foams for thermal management of batteries. FCC type structure gave a significant reduction in maximum temperature of battery by 12K compared to other structure. Furthermore, use of FCC and BCC type structures reduced the melting time of PCM by 28% and 26% respectively. Bai et al. [188] numerically investigated the effect of a cooling plate-PCM based cooling system on the thermal performance of the battery. A two-dimensional electro-thermal model was used to find the heat generation from a battery at various discharge rates. The cooling plate-PCM based cooling system improved the temperature uniformity within the battery pack and limited the temperature rise even at the 5C discharge rate. Variation of temperature within the battery pack with the height of the cooling plate was studied at 2C discharging rate. As the height of the cooling plate increased from 2cm to 7cm, the maximum temperature of battery pack first increased to a certain time, then decreased to a minimum value and again increased but attains constant value. Higher inlet mass flow rate of coolant resulted in efficient thermal management. In the similar manner, Youfu et al. [189] studied the effect of use of serpentine composite PCM (S-CPCM) plate in the cooling of Li-ion batteries. The cooling structure with S-CPCM plate was compared with block shaped CPCM (B-CPCM) structure. In this study, secondary cooling arrangement i.e. air cooling was also used to increase the efficiency of thermal management system. The results of this study evidently prove that the S-CPCM plate structure is better than the common B-CPCM module. The results also shows that thermal performance of the system also increases, as for the same fan power of 5.2 W the maximum temperature of batteries was 51.9°C in S-CPCM structure while 54.2°C in B-CPCM structure.

This section provides an overview regarding the use of PCM as a coolant for the thermal management of batteries. In this section, discussion has been made regarding the type of PCM which needs to be used for the BTMS and what specific properties are to be present in the PCM. Pure PCMs lack in thermal properties such as its thermal conductivity is low. The thermal properties of the pure PCM can be enhanced by the addition of nanoparticles in them. Table 5 summarizes the different PCM systems for cooling purposes and it can be seen that major systems used the composite PCM rather than pure PCM due to its high thermal properties. The enhancement of thermal properties of coolants such as liquid and PCM by the use of nanoparticle is discussed in detail in Section 5.

5. Use of nanomaterial in thermal properties enhancement

As discussed in Section 4 about different cooling strategies for the BTMS, it has been reported that the thermal properties of coolant play a vital role in the development of effective BTMS. It has been seen that cooling strategies shown in Section 4 can be improved if the thermal properties of respective coolants can be enhanced. In this section, the use of nanomaterial will be shown for the thermal properties enhancement of coolants such as Liquid and PCM. Literature review was done to find if thermal properties can be enhanced of air coolant by the use of nanomaterial but it is concluded that no relevant work was done in this direction. Therefore, this section gives an overview of the use of nanomaterials with Liquid and PCM coolant to enhance its thermal properties which in turn will be responsible for the improvement of the cooling efficiency of BTMS.

5.1. Use of nanomaterial in liquid coolant

Cooling performance of batteries cannot increase beyond a certain extent due to the limitation of lower thermal conductivity of liquid coolant (e.g., water and ethylene glycol) in comparison with metals. Several studies have been performed to bring battery temperature within the desired suitable range for battery packs. One way is to enhance the thermal conductivity of liquid coolants by adding metal at millimeter or micrometer-sized particles, but this strategy introduces certain issues such as difficulty in maintenance, complicated design of the system, and high cost of set up. This encouraged researchers to develop novel strategies for proper cooling [172]. To overcome these issues researchers proposed the use of Nano fluids to enhance the heat transfer performance by homogeneously mixing nano sized particles in liquid coolant [191]. Nanofluids were prepared by mixing nanoparticles (Al_2O_3, ZnO, CuO, TiO_2) with base fluids such as water and ethylene glycol. Li et al. [192] studied indirect liquid cooling using ZnO, TiO_2, and diamond-based nanofluids. It was observed that viscosities of all three and pure liquid remained nearly the same at a higher temperature but recorded an improvement in thermal conductivities and cooling performance due to a mixture of metal and pure coolant in comparison to only pure liquid. The best temperature decrement in Li-ion batteries,

Table 5
PCM based BTMS systems.

S. No.	PCM-system	Reference	Cell type (with some battery properties like Ah)	Battery Pack Configuration	PCM-type	Result/Inference
1.	Heat Pipe assisted PCM-based BTMS	• Huang et al. [183]	• 18650-type lithium ion cells used • Maximum charging current: 1.5A • Cell nominal voltage: 3.3V Cell nominal capacity: 100mAh	• 5 × 6 parallel configuration of cells • Nominal capacity of module: 33Ah • Maximum charging current of module: 45A • 4 Heat plates were placed after each set of 6 cells.	• Mixture of paraffin and expanded graphite (EG).	• Phase transition temperature and latent heat of PCM improves by addition of EG. • Addition of EG into paraffin improves thermal conductivity of PCM by six times even at high temperature of 50°C. • By the use of heat pipe assisted liquid based PCM system, the maximum temperature at 1C rate reduces by 1.19°C. While at 2C rate it reduces by 1.4°C and at 3C rate it reduces by 1.63°C.
		• Zhang et al. [184]	• $LiFePO_4$ cells (Prismatic shape) • Cell capacity: 2.7Ah • Nominal voltage: 3.2V	• Battery pack consists of 18 cells • 6S x 3P configuration • Battery pack capacity: 8.1Ah • Nominal voltage: 19.2V • Ten pieces of heat pipes used within battery pack	• Copper foam-paraffin composite • Addition of aluminum fins into copper foam	• Addition of aluminum fins into copper foams increases the natural heat transfer between battery pack and environment. • Maximum temperature of battery pack decreases by 1.1°C, 1.9°C, 2.6°C and 4°C respectively at 1C, 3C, 4C and 5C discharge rates with the use of heat pipe assisted system. • This system also improves the temperature uniformity within a single cell. • Temperature difference within a single cell doesn't increase above 5°C at any discharge conditions.
2.	PCM with tube shell battery pack	• Jiang et al. [185]	• 26650 type Li-ion cylindrical cells	• Five aluminum tubes arrayed in parallel configuration. • Each aluminum tube contains five cells connected in series.	• Paraffin + EG	• Maximum temperature difference across battery pack was less than 2°C. • Maximum temperature of battery reached to 72°C in case of forced air cooling without PCM, while in case of PCM maximum temperature reached only up to 51°C. • Baffles attached with aluminum tubes improved heat transfer. • Use of baffles doesn't decrease maximum temperature value, but reduce highest temperature region significantly.
3.	PCM with oscillating heat pipe based BTMS	• Wang et al. [186]	-	• Battery surrogate was used instead of real batteries. • Heating rods were used to heat up the battery surrogate by using DC current. • Oscillating heat pipes (OHP) were inserted between two battery surrogates.	Paraffin	• PCM based OHP BTMS and OHP based BTMS were compared at various power inputs. • In PCM based OHP system, system reached to targeted temperature i.e. 50°C at 874 sec, when input power was 25W. • But, in case of OHP based system heating time extended by 81.33% compared to PCM based OHP system for the same power input and targeted temperature.
4.	PCM with open cell metal foam	• Zhang et al. [187]	-	• Numerical model was made to study the • Electric heater was used to heat the container filled with PCM and aluminum foam.	• Paraffin + aluminum foam composite	• Two different aluminum foam structures made by body-centered cubic (BCC) and face-centered cubic (FCC) methods were used to evaluate heat transfer. • Structure with FCC type gave more temperature uniformity as compared to BCC type structure and pure PCM within battery. • Maximum temperature of battery with FCC structure reached only up to 338K, which was nearly 12K less than other two cases. • FCC type structure provides more flow resistance due to smaller pore size, which constrained natural heat convection.
5.	PCM-cooling plate based BTMS	• Bai et al. [188]	-	• Simulated model of battery was considered for analysis. • capacity of battery: 40Ah • specific heat of battery: 2138 J•kg-1•K-1 • density of battery: 1991 kgm-3	• Specific heat of PCM: 2,000 ($Jkg^{-1}K^{-1}$ • Latent heat of PCM: 247,000 Jkg^{-1} • Thermal conductivity of PCM: 0.151 $Wm^{-1}K^{-1}$ • Density of PCM: 778 kgm^{-3} • Viscosity of PCM: 0.01 $kgm^{-1}s^{-1}$	• Variation of temperature within battery pack with changing height of cooling plate was studied at 2C discharging rate. • As the height of cooling plate increased from 2cm to 7cm, maximum temperature of battery pack first increased to a certain time, then decreased to a min. value and again increased to relative stability index. • Maximum temperature increased as the space between adjacent batteries was increased from 3mm to 8mm.

(*continued on next page*)

Table 5 (*continued*)

S. No.	PCM-system	Reference	Cell type (with some battery properties like Ah)	Battery Pack Configuration	PCM-type	Result/Inference
						• Minimum and maximum temperature of battery pack decreased by 6K and 4K respectively as mass flow rate of coolant increased from 0.25×10^{-3} to 3×10^{-3} kgs^{-1}.
		• Youfu et al. [189]	• 32650 type Li-ion battery cells with nominal capacity of 5.8Ah.	• 3 modules with 32 cells. • Each module with 25.6V and 23.2Ah. • 8S4P cell configuration in each battery module. • Energy density of the battery module is 128.7 $Whkg^{-1}$.	• PCM was made up of hexadecane stearic acid and paraffin at a mass ratio of 11:1. Composite PCM (CPCM) used in this study was 5 wt% EG and 25 wt.% low-density polyethylene (LDPE).	• S-CPCM plate structure is better than the common B-CPCM module. • The S-CPCM structure reduces the weight of the CPCM module by approximately 70% and increased the energy density of the battery module. • For the same fan power of 5.2 W the maximum temperature of batteries was 51.9°C in S-CPCM structure while 54.2°C in B-CPCM structure.

Table 6
Comparison between different cooling strategies [29,190].

Performance criteria	Indirect liquid cooling	Direct liquid cooling	Forced air	PCM
Initial cost of set up	High	High	Low	Moderate
Maintenance of system	Medium	Difficult	Easy	Easy
Simplicity of using	Medium	Difficult	Easy	Easy
Heat transfer rate	Medium	High	Low	High
Ease of integration	Difficult	Difficult	Easy	Easy
Viscosity of coolant	Medium (e.g., Water)	High (e.g., Mineral oils)	low	Medium
Life	About 20 years	3-5 years	About 20 years	About 20 years

Table 7
Comparative study of different Nano-fluids and their impact.

Nanoparticle	Base fluids	Result of Study	Reference
ZnO	Distilled Water - Ethylene Glycol mixture	• Viscosity nearly same as pure fluid at high temperature Thermal conductivity more than pure fluid and remains unchanged with respect to temperature	[192]
TiO_2	Distilled Water - Ethylene Glycol mixture	Viscosity nearly same as pure fluid at high temperature Thermal conductivity first decreases then increases on variation with temperature	[192]
Diamond	Distilled Water - Ethylene Glycol mixture	• Viscosity nearly same as pure fluid at high temperature Record temperature decrement by nearly 13.2°C of Li-ion battery	[192]
Al_2O_3	Water	• For Li-ion battery 1.5wt% Al_2O_3 water Nano fluid, heat exchanger capacity increased by 37.5% after adding Nano fluid	[193]
Al_2O_3	Water - Ethylene glycol mixture	• With 0.5% (volume concentrations) Al_2O_3, thermal conductivity 0.05 $Wm^{-1}K^{-1}$ higher than based fluid	[194]
CuO	Deionised water	• Thermal conductivity enhanced by 12.4% of CuO Nano fluid as compared to deionised water.	[195]
CuO	Water	• Thermal conductivity enhanced by 5.5% as compared to water.	[196]

by nearly 13.2°C, was recorded with diamond-based nanofluid in comparison with pure liquid coolant. Table 7 presents different nanofluids prepared by a combination of various nanoparticles such as ZnO, TiO_2, Al_2O_3, CuO, with base fluids such as water and ethylene glycol for improvement in thermal conductivity. It is also suggested that this strategy will finally improve the performance of coolant in thermal management. Huo et al. [193] considered Al_2O_3 nanoparticle mixed with water as base fluid and it was observed that heat exchanger capacity increased by 37.5% after considering nanofluid. Another study on Al_20_3 nanoparticle was done by Zakaria et al. [194] with water-ethylene glycol mixture as base fluid and observed that with 0.5% (volume concentrations) Al_2O_3, the thermal conductivity gets enhanced. It was reported in the results that the thermal conductivity of the resulting nanofluid was 0.05 $Wm^{-1}K^{-1}$ higher than based fluid. Manimaran et al. [195] demonstrated improvement in thermal conductivity by 12.4% in nanofluid prepared by CuO nanoparticle mixed with deionized water when compared with only deionized water as the coolant. CuO nanoparticle was also studied by Patel et al. [196] with water as base fluid and it was noticed that the thermal conductivity of nanofluid was about 5.5% higher as compared to the base fluid. Recent work on nanofluids in the BTMS was done by Yang et al. [197]. They observed an influence on heat dissipation performance due to flow path variation by inlet and outlet position in parallel liquid cooling strategy.

Temperature has an adverse effect on the performance of batteries; therefore a suitable thermal management system is required. Also, it is needed that the complexity and the energy consumption of the system should be minimum with maximum thermal performance. Apart from the design of the cooling system, coolant plays a major role in the battery cooling. Therefore, it is demanded that coolant should have significant thermal properties, as pure coolants like water do not have considerable thermal properties that are needed for the adverse ambient environment. To solve these issues researchers studied the use of nanomaterial in the coolant for increasing its thermal performance. Table 7 summarizes the use of different nanoparticles for thermal properties enhancement of the base fluids. Through these studies, it can be concluded that the use of nanomaterial in the base coolant has the potential for enhancement of the thermal management system. After reviewing the studies pertaining to the use of nanomaterial in liquid coolant, it can be concluded that for the wider utility of nanofluids along with liquid based coolant more research needs to be done in the area of nanofluids to enhance its thermal performance and heat transfer rate, reducing its initial set up cost, ease of application, simplicity to adapt and prolonged life of thermal management system.

5.2. Use of nanomaterial in PCM-based coolant

As discussed in previous section, despite of PCM characteristics such as high heat-storing capacity and lightweight; one of the major concerns with the use of PCM is their low thermal conductivity. Many researchers have worked to improve PCM's thermal conductivity by the use of additive materials in them to form a PCM composite. Addition of different types of additives into PCM to enhance the thermal conductivity of PCM is classified as below [198].

5.2.1. Addition of thermal conductive additives

Thermal conductivity of a PCM can be significantly improved by the addition of thermal conductive materials such as carbon fiber, graphene, carbon nanotubes (CNT), etc. [199–201]. Hamada et al. [199] investigated the enhancement in the thermal conductivity of PCM by the addition of carbon-fiber chips and carbon brushes. Three types of carbon fiber chips i.e. CFL (carbon fiber of low thermal conductivity of 5 $Wm^{-1}K^{-1}$), CFM (carbon fiber of middle thermal conductivity of 190 $Wm^{-1}K^{-1}$), and CFH (carbon fiber of high thermal conductivity of 500$Wm^{-1}K^{-1}$) were used to study the thermal conductivity enhancement of PCM used. Results showed that a combination of CFL and CFH in volume fraction of 0.014% and 0.005 % by volume respectively, made a significant increase in thermal conductivity of PCM by about 230%. Frusteri et al. [200] studied the effect of carbon fibers on the enhancement of thermal conductivity of inorganic PCM44. Experimental study was done to study the effect of the addition of carbon fiber in different compositions in PCM. A significant increase in thermal conductivity by about 360% was observed when carbon nanofiber was added in 10% by weight concentration in PCM. Some other significant studies were done to find out the potential use of carbon nano-fiber and carbon nanotubes for the thermal performance enhancement of PCM. Cui et al. [201] studied the thermal properties of carbon nano-fiber (CNF) and carbon nanotube (CNT) based PCM composites experimentally. The thermal conductivity of paraffin increases from 0.32 $Wm^{-1}K^{-1}$ to 0.45 $Wm^{-1}K^{-1}$ on the addition of CNF 10% by weight. Paraffin is one of the most used PCM in different studies by researchers; studies were performed for the enhancement of its thermal conductivity by the addition of different additives in it. Goli et al. [202] found a significant increase in thermal conductivity of paraffin from 0.25 $Wm^{-1}K^{-1}$ to 0.5 $Wm^{-1}K^{-1}$ when 1% by weight graphene was added to paraffin. Incorporation of graphene into paraffin also leads to a significant decrease in a temperature rise of Li-ion batteries. Shi et al. [203] also studied the effect of graphene in improving the thermal performance of PCM. PCM composite was developed by mixing paraffin with graphene in a toluene mixture and graphene concentration was varied from 1 to 10 by weight percentage of the composite. Results showed an increase in thermal conductivity ranging from 0.26 to 0.5 $Wm^{-1}K^{-1}$ according to graphene concentration. Some researchers studied the effect of carbon nano-fiber on the thermal performance of paraffin. Elgafy et al. [204] studied the thermal performance of CNF filled paraffin wax experimentally as well as analytically. One dimensional heat conduction approach was considered to predict the thermal conductivity of the PCM composite. A significant increase in thermal conductivity by 37% was observed in PCM composite. Yavari et al. [205] studied the variation in thermal conductivity of PCM composite made by mixing 1-octadecanol and graphene. The thermal conductivity of PCM increased from 0.38 $Wm^{-1}K^{-1}$ to 0.91 $Wm^{-1}K^{-1}$ by the addition of 4% graphene by weight in 1-octadecanol. A significant study was performed by Choi et al. [206]; they analyzed the addition of carbon additives like Multi-walled carbon nanotubes (MWCNT), graphene, and graphite in PCM. Furthermore, the effect of Poly Vinyl Polyvinylpyrrolidone (PVP), as a dispersion stabilizer, was investigated on the thermal conductivity of PCM. Effective thermal conductivity of PCM increased by 15.2%, 8.79%, and 8.27% respectively by the addition of graphene, graphite, and MWCNT at 0.1 volume percentage without the use of PVP. The addition of PVP improved dispersion stability of nanoparticles into PCM. When PVP was added into PCM, effective thermal conductivity increased by 21.5%, 10.5%, and 9.91% for graphene, MWCNT, and graphite respectively. Xiao et al. [207] created the solid-solid polymer PCM (SSPoPCM) and studied the effect of addition of EG additives in the enhancements of thermal properties. The SSPoPCM was developed by adding aliphatic chains with cross linked polymeric skeleton through chemical bonding. The effect of addition of different wt.% of EG in SSPoPCM was studied and it was found that the thermal conductivity increased by 490%, 677% and 753% for 4%, 6% and 8% EG in SSPoPCM respectively with respect to pure paraffin.

After a detailed study of Table 8, it can be concluded that the addition of thermally conductive materials like CNF, graphene, etc. into PCM gives a significant increase in thermal conductivity of PCM, which subsequently results in into effective thermal performance of battery pack.

5.2.2. Impregnation of PCMs into porous metal foam and carbon foam matrices

Impregnation of PCM into metal and carbon foam matrices is another way of incorporating nanomaterial to improve the thermal conductivity of PCM. Table 9 summarizes various works done by different researchers to form PCM based composite by impregnating PCM into different carbon foam matrices. Many researchers studied the incorporation of expanded graphite (EG) in different weight concentration into PCM. Gilart et al. [209] fabricated paraffin-graphite foam composite to improve the thermal conductivity of paraffin. Various methods like X-ray diffraction (XRD), Raman spectroscopy, and Scanning Electron Microscopy (SEM) was used to understand the microstructural changes occurring within graphite during the expansion processes. Surface area of graphite increased by 1267% using Mill's expansion process and the significant increase in thermal conductivity by about 576% was observed. It was also reported from the results that almost 1100% increase in thermal conductivity was observed when the mass fraction of paraffin was reduced to 50%. In a similar way, Li et al. [210] investigated the effect of the addition of EG into paraffin at different concentrations. It was observed from the results that the thermal conductivity of PCM increased significantly up to 41% when EG was mixed by 20% weight concentration in paraffin. From these two studies, made on paraffin-EG foam composite, it can be concluded that increasing the concentration of any additive into PCM results in an increase in its thermal conductivity. Sari et al. [211] studied the impregnation of palmitic acid into EG to enhance the thermal properties of PCM. A significant increase in thermal conductivity of up to 250% was reported in the palmitic acid when EG was added by 20% weight concentration. Chen et al. [212] studied morphology and microstructural characterization of different Graphite Nanosheets (GN) such as randomly distributed graphite Nanosheets (R-GN) and oriented graphite Nanosheets (O-GN), reinforced into paraffin at various loadings and their effect on heat transfer and thermal conductivity. Furthermore, enhancement in thermal conductivity was compared between R-GN and O-GN paraffin composite at various loading. It was reported that the thermal conductivity of O-GN based composite increased up to 1.68 $Wm^{-1}K^{-1}$ whereas increment was about 4.47 $Wm^{-1}K^{-1}$ in the case of R-GN based PCM composite at 5% GN loading. Ji et al. [213] found a significant increase of about 1800% in thermal conductivity of PCM i.e. paraffin by loading it with annealed ultrathin graphite foam (UGF). Addition of UGF with paraffin improved cycle stability with negligible change in PCM melting temperatures. Some researchers also studied the potential use of different PCM apart from paraffin and the method for its thermal performance enhancement. Li et al. [214] investigated the effect of spongy graphene on thermal conductivity and latent heat of Docosane, used as a PCM. Different methods like Fourier-transform infrared spectrometer, X-ray diffractometer, and SEM were used to study the microstructural changes in docosane. It was noticed that due to the presence of spongy graphene, highly crystalline layered docosane was formed which increased latent heat and thermal conductivity of docosane. Thermal conductivity and latent heat of docosane increase from 0.26 to 0.59 $Wm^{-1}K^{-1}$ and 256.1 to 262.2 Jg^{-1} respectively by impregnating it into spongy graphene. Xiao et al. [215] studied the

Table 8
Enhancement of thermal conductivity of PCM by thermal conductive additives.

S. No.	References	PCM + Additive	Thermal conductivity (Pure PCM) $Wm^{-1}K^{-1}$	Thermal conductivity (Composite) $Wm^{-1}K^{-1}$	Ratio of Composite % wt./ by volume	Increase in thermal conductivity (in %)
1	Shi et al. [203]	Paraffin + Graphene	0.25	0.26-0.5	1-10	4 - 100
2	Ye et al. [208]	Paraffin + Graphene	0.207	0.274	3	32.36
3	Goli et al. [202]	Paraffin + graphene	0.25	0.5	1	100
5	Elgafy and Lafdi [204]	Paraffin + CNF	0.24	0.25-0.33	-	4.17 - 37.5
6	Yaveri et al. [205]	1- octadecanol +graphene	0.38	0.91	4	139
7	Frusteri et al. [200]	PCM 44 + carbon fiber	0.47	2.2	10	368
8	Cui et al. [201]	Paraffin + CNF	0.32	0.45	10	40.6
9	Hamada et al. [199]	1-octadecanol + carbon fiber chips	0.34	1.12	0.014	229
10	Choi et al. [206]	Stearic acid + graphite flakes (GFI)	0.26	0.28-0.75	0.1-1	7.69 - 188
		Stearic acid + graphene	0.26	0.31-0.35	0.1-1	19.23 – 34.61
		Stearic acid + MWCNT	0.26	0.286-0.45	0.1-1	10 - 73
11	Changren Xiao et al. [207]	SSPoPCM/EG-4%	0.3	1.77	4	490
		SSPoPCM/EG-6%	0.3	2.33	6	677
		SSPoPCM/EG-8%	0.3	2.56	8	753

Table 9
Enhancement of thermal conductivity of PCM by impregnating PCM into Carbon foam.

S. No.	References	PCM+ Additive	Thermal conductivity (Pure PCM) $Wm^{-1}K^{-1}$	Thermal conductivity (Composite) $Wm^{-1}K^{-1}$	Ratio of Composite % wt./ %vol.	Increase in thermal conductivity (in %)
1	Sari and Karaipekli [211]	Palmitic Acid + EG	0.17	0.60	20	253
2	Gilart et al. [209]	Paraffin + EG	0.38	2.55	25	571
3	Chen et al. [212]	Paraffin+ graphite Nano sheets	0.2	0.33-4.47	0.1-5.0	65 - 2135
4	Li et al. [210]	Paraffin + EG	0.32	0.71-14	2-20	122 - 4275
5	Ji et al. [213]	Paraffin + ultrathin graphite foam	0.2	1.8-3.7	0.8-1.2	800 - 1750
6	Xiao et al. [215]	Paraffin + carbon foam	0.354	1.198	-	238
7	Li et al. [214]	Docosane + spongy graphene	0.26	0.59	0.3	127

thermo-physical properties of paraffin-carbon foam composite by vacuum assistance method. Differential scanning calorimeter was used to investigate the thermal behavior of PCM. Results showed that effective thermal conductivity of PCM significantly increases from 0.354 to 1.198 $Wm^{-1}K^{-1}$. It was noticed that the use of porous carbon foam improved the thermal effusivity of paraffin from 0.796 to 1.284 ($KJm^{-2}K^{-1}s^{-1/2}$). It can be concluded from the studies reviewed here that the impregnation of PCM into carbon foam significantly improves the thermal conductivity of PCM. The concentration of carbon foam in PCM also plays an important role in the enhancement of thermal conductivity of PCM. Impregnation of PCM into carbon foam also improves other thermo-physical properties of PCM like cycle stability and thermal effusivity etc.

Metals foams like aluminum foam, nickel foam, and copper foams have been studied to develop PCM based composites due to their properties like high thermal conductivity, high porosity, and high specific strength. Generally, metal foams have porosity ranging from 80-98%. A large amount of PCM can be impregnated into metal foams due

Table 10
Enhancement of thermal conductivity by impregnating PCM into the metal foam.

S. No	References	PCM+ Additive	Thermal conductivity (Pure PCM) $Wm^{-1}K^{-1}$	Thermal conductivity (Composite) $Wm^{-1}K^{-1}$	Porosity (%)	Pore size (mm/PPI)	% increase in thermal conductivity
1	Xiao et al. [216]	Paraffin + copper foam	0.354	4.98	96.8	5	1306
			0.354	5.40	96.5	3	1425
			0.354	5.04	97	1	1323
			0.354	11.33	92	1	3100
			0.354	16.01	89	1	4422
2	Xiao et al. [216]	Paraffin + nickel foam	0.354	1.22	97.4	5	244
			0.354	1.21	97.5	3	241
			0.354	1.24	97	1	250
			0.354	1.07	94	1	202
			0.354	2.33	91	1	558
3	Hong et al. [217]	Paraffin + aluminum foam	0.52	10.9	92	2	1996
			0.52	10.4	93	1	1900
			0.52	16.2	93	0.5	3015
4	Fleming et al. [218]	Water + aluminum foam	0.56(liquid)	1.8	94.5	40	221
5	Feng et al. [219]	Water + copper foam	0.56(liquid)	3.47	96	8	519
			0.56 (liquid)	1.95	98	8	248

to its high porosity values. Table 10 summarizes the studies which reported the enhancement of thermal conductivity of PCM by impregnating them into metal foams. Xiao et al. [216] used copper and nickel foams at various porosity concentrations and pore sizes to investigate the enhancement of thermal conductivity of paraffin as shown in Table 10. Effective thermal conductivity of paraffin-copper foam composites increased up to 16.01 $Wm^{-1}K^{-1}$ with 89% porosity compared to 0.354 $Wm^{-1}K^{-1}$, of pure paraffin. In the case of paraffin-nickel based PCM composite, the effective thermal conductivity increases up to 2.33 $Wm^{-1}K^{-1}$ with 91% porosity. After analyzing the results, it can be concluded that the copper foam gave a more significant increase in thermal conductivity as compared to nickel foam. Furthermore from the results, it was identified that the effective thermal conductivity of composite decreases as the porosity of metal foam increases. Hong et al. [217] studied the effect of impregnation of paraffin in aluminum foam on its thermal conductivity at different pore sizes and porosity levels. The effective thermal conductivity reached up to 16.2 $Wm^{-1}K^{-1}$ compared to 0.52 $Wm^{-1}K^{-1}$ of pure paraffin at 93% porous aluminum and pore size of about 0.5 $mmPPI^{-1}$. It was evident from the results that the effective thermal conductivity increases with a decrease in porosity level. Few researchers also used water as PCM and studied its thermal performance by impregnating it with metal foam. Fleming et al. [218] studied the thermal characteristics enhancement of the water-aluminum foam-based PCM composite. The effective thermal conductivity increased from 0.56 $Wm^{-1}K^{-1}$ to 1.8 $Wm^{-1}K^{-1}$ by impregnating water (in liquid state) into 94.5% porous aluminum. Similarly, Feng et al. [219] developed a PCM – metal foam based composite by taking water as a PCM. Copper foam was used at different porosity levels to enhance the thermal conductivity of water and results showed a significant increase in thermal conductivity by about 519% at 96% porosity level of copper foam. It can be concluded from the above studies that the impregnation of PCM into metal foam greatly improves the thermal conductivity of PCM. Porosity level as well as pore size of metal foam also plays an important role in the enhancement of thermal conductivity of PCM. Furthermore, it is evident from the results that the thermal conductivity of PCM-metal foam composite increases as the porosity level of metal foam decreases.

The above studies show that the addition of nanomaterial in PCM eliminates the drawback associated with it i.e. its low thermal conductivity. Incorporation of nanomaterials into PCM not only improved their thermal conductivity but also improved temperature uniformity within battery pack which results in an effective thermal management system.

From the review of the studies presented in Section 5.2.1 and 5.2.2, it can be concluded that the incorporation of nanomaterial in the pure PCM enhanced its thermal performance which finally results in better thermal management of batteries. Different types of nanomaterials and its methods of addition in PCM were reviewed in the previous section. It is also important to study the application of PCM composite in the battery pack and to see the effect of the thermal behavior of batteries. Therefore, the application of composite PCM in BTMS is shown in Section 5.3.

5.3. Potential applicability of composite PCM in BTMS

PCM is widely used for the thermal management of battery packs due to their large heat storing capacity. Pure PCM doesn't have a high value of thermal conductivity [220], which restrict their use for an effective thermal management system. The use of nanomaterial with pure PCM enhanced its thermal behavior as discussed in Section 5.2.1 and 5.2.2. This section focuses on the incorporation of PCM composite in a different battery pack system. Table 11 summarizes the studies done by different researchers using the PCM composite in the thermal management of the battery pack and also the effectiveness of PCM composite is shown in comparison to pure PCM. Sabbah et al. [158] have shown the comparative study between the air-cooled system and PCM cooling system in which the micro-composite graphite-PCM matrix was used.

Table 11
PCM Composites in different BTMS study.

S. No.	References	PCM composite properties	Battery pack configuration	Results/ Inference
1	Khateeb et al. [178]	PCM & Al-foam $k_{Al} = 218$ $Wm^{-1}K^{-1}$ $k_{pcm} = 0.21$ $Wm^{-1}K^{-1}$ (liquid state) $k_{pcm} = 0.29$ $Wm^{-1}K^{-1}$ (solid state)	• Eighteen 18650 cylindrical cells • Cell capacity: 2.2 Ah • 3S x 6P configuration	• Use of aluminum foam with PCM causes a temperature drop of about 50% compared to case of no thermal management. A significant temperature drop of 15°C with use of PCM compared to case of no thermal management.
2	Sabbah et al. [158]	PCM & graphite $k_{eff} = 16.6$ $Wm^{-1}K^{-1}$ $Cp_{eff} = 1980$ $Jkg^{-1}K^{-1}$	• 68 modules • Each module: Twenty 1.5Ah type 18650 cells 4S x 5P configuration	• In the case of PCM-based cooling system, the temperature of battery was under safety limit (52°C) at ambient temperature of 45°C and discharge rate of 6.67C. • Temperature uniformity also increases while without requiring any extra fan power.
3	Kim et al. [222]	PCM & graphite	• Twenty 18650 Li-ion cells • 4S x 5P configuration Battery capacity: 7.5Ah	• Three cooling methods were studied- only air-based cooling, only PCM-based cooling, and PCM-air based cooling. • Study was done by analyzing battery pack temperature on different drive cycles such as US06, Aggressive, etc. • For US06 drive cycling, the steady state temperature for both the air cooling methods was about 40°C while in only PCM-based cooling, temperature may rise greater than 65°C. Heat rejection rate was found not so effective in PCM-based cooling in comparison with forced air cooling due to less exposed cooling surface.
4	Kizilel et al. [221]	PCM & graphite $K_{eff} = 16.6$ $Wm^{-1}K^{-1}$ $C_p = 1980$ $JKg^{-1}K^{-1}$	• 67 modules • Each module: twenty 18650 high power cell • 4S x 5P configuration • Module capacity: 7.5Ah	• Temperature uniformity was better in PCM cooling as the temperature difference between 2 adjacent cells was only about 0.2°C while in air cooling it was about 3°C. • Due to the high thermal conductivity of PCM composite matrix heat

(continued on next page)

Table 11 (*continued*)

S. No.	References	PCM composite properties	Battery pack configuration	Results/ Inference
				spreading was fast in comparison to air cooling which reduces the thermal runaway chances.

Their study revealed that in the case of PCM based cooling system, the temperature of the battery pack was under a safe limit (55°C) at an ambient temperature of about 45°C or even up to 52°C and discharge rate of about 6.67C (10A/cell). It was also noticed that the uniformity of temperature in the battery pack increased without requiring any extra fan power, while the air-cooled system requires more fan power to deliver this much cooling effectiveness. Kizilel [221] also investigated the effectiveness of PCM composite, consisting of graphene and paraffin. Comparison of passive cooling by PCM composite was done with active cooling by forced air or natural convection. Different comparative analyses were done between both cooling strategies such as temperature uniformity was studied between two adjacent cells and it was noticed that surface temperature of batteries reached up to 60°C and the temperature difference was as high as 3°C. On the other hand, temperature uniformity was observed to be good in the case of PCM-based cooling, as temperature difference between the cells was about 0.2°C. It was also concluded that PCM can have safety advantage over air cooling, as in the case of air cooling, failure of individual cell at $t = 0$sec leads to the propagation of thermal runaway throughout the battery pack. While in PCM cooling, thermal runaway does not propagate and the temperature of batteries remains near ambient temperature because PCM-graphite matrix absorbs and spreads heat very quickly due to its high thermal conductivity. Kim et al. [222] studied the effectiveness of PCM/graphite matrix in BTMS by comparing it with the air cooling technique. Three cooling methods were studied such as only air-based cooling; only PCM-based cooling and PCM-air based cooling. Study was done on different drive cycles such as US06, Aggressive cycles and for the study of high energy density cells, virtual battery modules were developed. US06 and Aggressive cycling showed similar results in both the cases i.e. air cooled-PCM and only air cooling methods and both the methods had a periodic temperature of about 40°C. But in the case of only PCM-based cooling, heat accumulated in the system due to insufficient heat removal which caused the steady-state temperature to rise to 65°C. Results of virtual module testing also showed that the use of PCM significantly reduces the temperature rise of batteries but it needs some time for heat removal since the heat transfer is not effective due to less exposed cooling surface. Therefore, it was concluded that the use of passive PCM-based cooling with the active cooling like air cooling will become more effective cooling method. In the thermal management study, Khateeb et al. [178] used a PCM based composite material consisting of PCM and Aluminum foam. Study was performed on the Li-ion battery pack used in electric scooters, where battery pack contained eighteen 18650 cylindrical cells arranged in 3 series x 6 parallel configuration. For the analysis of temperature distribution within battery pack 2-D thermal model was used. Results showed that the use of aluminium foam with PCM made the temperature drop to about 15°C as compared to the case when no thermal management system was incorporated. Along with the temperature drop, the temperature distribution among the battery pack was also enhanced.

After observing the review analysis of Table 11 and detailed study of all the mentioned work, it can be concluded that the use additives in PCM enhanced its thermal conductivity and furthermore the use of composite PCM-based cooling methods have several advantages over other alternative cooling techniques for BTMS. From the studies, this can be concluded that PCM-based cooling offers more temperature control and uniform temperature distribution due to its phase change capability. But this passive cooling strategy will work far better if coupled with other active cooling methods such as air cooling. It will increase the heat rejection rate which in turn will result in uniform temperature distribution within the battery pack.

6. Conclusion

Li-ion batteries are widely used in EVs. But the major concern with the use of these batteries is the rise of temperature due to uncontrolled chemical reactions within the battery pack at extreme temperature conditions. Thus, a proper thermal management system is required to improve the thermal performance of batteries. In this review, different types of available batteries are discussed but the secondary batteries are mainly focused on due to their rechargeable feature and easy availability in the market. Battery characteristics such as electrical, thermal, and chemical are investigated in this review and the methods of modeling of thermal characteristics have been explored. For the development of BTMS, this review collates the different cooling strategies such as air, liquid, PCM-based cooling and a method has been explored for increasing the efficiency of these strategies. The different possible ways of using the nanomaterial in these strategies and its effect on the improvement of the efficiency of BTMS had been analyzed. All these different studies were gathered; put together and based on the results detailed analysis was done. In this review, based on these analysis authors tried to identify the future possible works in this field. The summary of the conclusion for this review study is as follows:

- Li-ion batteries were identified as the most suitable for this study due to its advantageous characteristics and wide applicability such as EVs, energy storage devices, etc. among different battery chemistries.
- The different battery characteristics such as electrical, thermal, and chemical were analyzed and an effort was made to correlate the effect of these characteristics on the thermal behavior of batteries. The different methods for heat generation and heat dissipation modeling were analyzed for the accurate study of thermal characteristics of Li-ion battery.
- To solve the thermal issues of BTMS, different strategies such as air, liquid, and PCM-based cooling were analyzed. The advantages, disadvantages, and applicability of the air cooling system based on its thermal efficiency were analyzed. Further areas were identified where work can be done for the improvement of thermal efficiency.
- Different designs of liquid cooling systems were analyzed according to the requirements of different systems. It was identified from various studies that components such as the cooling channel affect the thermal performance. It is concluded that work needs to be done to make the designing of a liquid cooling system less complex and safer.
- PCM based cooling system was analyzed as the alternative solution to the areas where air and liquid cooling system is less efficient. The different systems such as heat pipe assisted PCM based BTMS, PCM with open-cell metal foam, PCM-cooling plate-based BTMS, etc. were analyzed as the potential application for the use of PCM based cooling system. The low thermal conductivity of pure PCM was identified as the main problem in the application of this cooling strategy.
- The use of nanomaterial in the liquid coolant and PCM were analyzed for the enhancement of thermal properties. The methods of the addition of nanomaterial in PCM and the potential applicability of composite PCM in BTMS were explored.
- It can be concluded that the future scope lies in exploring more regarding the use of nanomaterial in liquid coolants for BTMS. Further explorations are needed for the usage of nano-particles in air coolant for increasing their thermal performance.

Declaration of Competing Interest

The authors have NO affiliations with or involvement in any organization or entity with any Financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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