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Review Article

A review on battery thermal management strategies in lithium-ion and post-lithium batteries for electric vehicles

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ABSTRACT

Electrification on transportation and electricity generation via renewable sources play a vital role to diminish the effects of energy usage on the environment. Transition from the conventional fuels to renewables for transportation and electricity generation demands the storage of electricity in great capacities with desired power densities and relatively high C-rate values. Yet, thermal and electrical characteristics vary greatly depending on the chemistry and structure of battery cells. At this point, lithium-ion (Li-ion) batteries are more suitable in most applications due to their superiorities such as long lifetime, high recyclability, and capacities. However, exothermic electrochemical reactions yield temperature to increase suddenly which affects the degradation in cells, ageing, and electrochemical reaction kinetics. Therefore, strict temperature control increases battery lifetime and eliminates undesired situations such as layer degradation and thermal runaway. In the literature, there are many distinct battery thermal management strategies to effectively control battery cell temperatures. These strategies vary based on the geometrical form, size, capacity, and chemistry of the battery cells. Here, we focus on proposed battery thermal management strategies and current applications in the electric vehicle (EV) industry. In this review, various battery thermal management strategies are documented and compared in detail with respect to geometry, thermal uniformity, coolant type and heat transfer methodology for Li-ion and post-lithium batteries.

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INTRODUCTION

Carbon footprint and harmful emissions related to transportation can be decreased greatly if the fossil fuel vehicles are replaced with electric vehicles (EV), especially if the electricity is generated via renewable energy sources (i.e., no emission for travel, emissions would be limited with the ones related with production). Hence, storing electricity in huge capacities becomes essential which triggers advanced battery technologies to be developed to satisfy the demand in energy storage and EV industries

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[1, 2]. International Energy Agency has recently reported that many developed countries abandon fossil fuel vehicles, electrified technologies are financially and politically supported and even this changeover is getting mandatory according to the regulations on carbon emission [3]. In addition, European Commission funds the green (technologies with minimum effect on the environment) the electric vehicle and innovative energy storage technologies under Horizon 2020 calls [4-6]. Even if various chemical types of batteries such as lead-acid [7-9] and nickel-cadmium (NiCd) [10-12] are used in EV and hybrid electric vehicle (HEV) industries, Li-ion batteries are generally preferred due to their superiorities on energy density, lighter weight, and high recyclability [13, 14].

Li-ion batteries are rechargeable power sources in which stored chemical energy is converted to electricity. The geometric form of the Li-ion batteries may be cylindrical, pouch type, and prismatic. Although the chemistry of the Li-ion batteries may vary according to the application area and desired performance, the main components of the battery cells are the same. Each type of Li-ion battery includes high conductive current collectors, anode and cathode layers (electrodes), electrolyte, tabs, and porous separator (Figure 1). In Li-ion batteries, carbon-based porous materials (graphite) are used as the anode while the cathode layer contains a lithium-metal-oxide compound [15]. Cylindrical Li-ion cells have high energy density and compact form; however, the only end-user of cylindrical battery packs is Tesla Inc. company. Note that the 1865, 2170, and 4680 types of cylindrical batteries are the most preferred ones. Here first two digits represent the diameter and the next denotes the height of the battery cell. On the other hand, thermal management of the cylindrical battery packs is more complicated compared to other battery cell types. Pouch type Li-ion battery cells have alternative compact designs allowing strict thermal management due to their adequate heat transfer surfaces. However, the main shortcoming of pouch cells is their lower energy storage capacity than the prismatic type batteries.

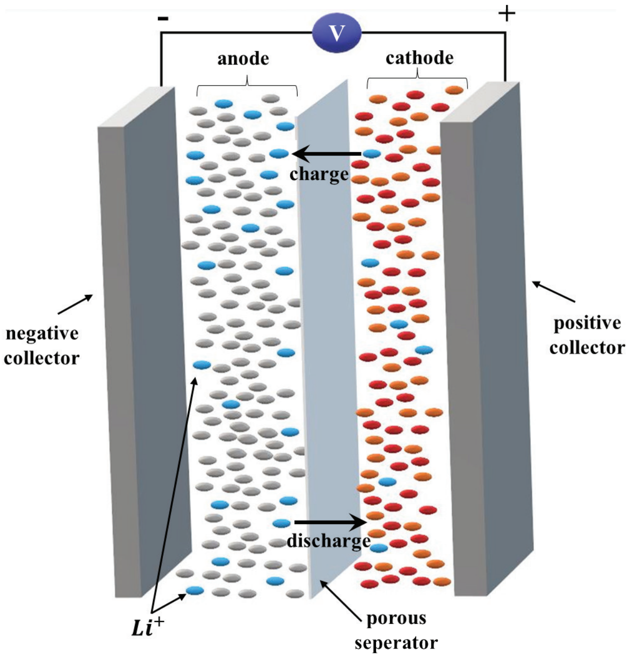

Figure 1. Main sublayers of a Li-ion battery cell.

Nowadays, high-capacity prismatic cells are mostly preferred type of Li-ion batteries, especially for high-power electric vehicles. Note that, cell thickness of the prismatic Li-ion batteries is at least two or three times larger than pouch ones, yet pouch type batteries are named as prismatic batteries in some EV battery specifications. The main disadvantage of the prismatic batteries in comparison to pouch cells is having limited heat transfer surface area for the same battery capacity. Therefore, high-capacity pouch type batteries are the prime candidate for the near future electric vehicle battery pack technologies. In addition to geometrical forms, material-based battery electrochemistry is another scientific research area. There are many electrochemical and physical Li-ion/Li-polymer battery research for cathode materials of Lithium Manganese Oxide (LMO) [16, 17], Lithium Titanate Oxide (LTO) [18-20], Lithium Cobalt Oxide (LCO) [21, 22], Lithium Iron Phosphate (LFP) [23-25], Lithium Nickel Manganese Cobalt Oxide (NCM) [26-28], and Lithium Nickel Cobalt Aluminium Oxide (NCA) [29, 30]. Although the Li-ion and Li-polymer batteries are similar in terms of the electrochemistry, the main difference among them is the electrolyte type. Li-ion batteries include liquid electrolyte, whereas Li-polymer batteries have solid or semisolid polymer-based electrolyte layers.

The batteries are utilized in many crucial applications such as electric vehicles, hybrid energy systems [31, 32], and photovoltaic-thermal technique [33]. In this paper, we mainly focus on the electric vehicle battery pack and thermal management applications for the Li-ion and post-lithium batteries. At this point, we should clearly cover the heat generation mechanism and the physics behind this phenomenon. Heat generation within a Li-ion battery cell contains three main concepts [34, 35]: electrochemical reactions, Joule heating, and anode-cathode side reactions [36, 37]. Determination of the heat generation characteristics is also essential to achieve effective and strict thermal management for electric vehicles [38]. Therefore, understanding the heat generation and thermal characteristic phenomena for each type of battery cell and measurement of the heat generation at different C-rates are crucial for an adequate thermal design [39-41]. The general form of the heat generation equation (known as Bernardi equation in the literature) is given by [42-44]:

$$\dot{q} = I(V_0 - V_C) - IT\frac{dV_0}{dT} \tag{1}$$

where $\dot{q}, I, V_0, V_C$ and T is the heat generation rate, circuit current, open-circuit voltage, cell voltage and battery temperature, respectively. Heat generation within the battery cells and packs is non-uniform. The reason behind this physics is that current flows through the tab locations and more heat is being generated in the vicinity of battery tabs. Furthermore, experimental investigations indicated that the temperature level is greater towards the negative tab during the charging process [45]. In contrast, positive tab region overheats when the battery is discharged. Moreover, the temperature differences between the battery tab and battery surfaces (temperature along the battery thickness cannot be considered as uniform and it varies with thickness) also increase with the current rate (C-rate). C-rate is the measure of how fast batteries are charged/discharged, i.e., 1C corresponds a battery cell can be charged/discharged within 1 hour, and this operation decreases to 30 minutes at 2C.

Nowadays, main demands of EV users are fast charging, passenger safety, and longer milage range. Yet, fast charging at high C-rates, greater than 2C, leads to overheating within the battery cells and battery pack. Note that the batteries in a module cause to generate approximately %22 larger amount of heat due to the interconnections between the cells compared to single cell [46]. Therefore, battery thermal management systems (BTMS) should be capable of transferring the generated heat within the battery systems and to keep the temperature level within an optimal range. Otherwise, temperature of the battery pack proceeds increasing which accelerates the batteries ageing and capacity fade. Furthermore, electric vehicles may expose to the thermal runaway condition which is a critical safety problem [47, 48] in the EV industry. Thermal runaway is a chain electrochemical reaction [49, 50], and it may cause fire, hazardous emissions, and explosion. Therefore, a BTMS should satisfy the adequate thermal control requirements in order to prevent these safety risks and decrease the capacity fade. Pesaran [51, 52] one of the pioneer researcher on the battery thermal control strategies revealed that BTMS designs should have four essential assignments: cooling to remove heat from the batteries and to obtain uniform temperature distribution in battery pack, ventilation to exhaust the potentially hazardous gases when needed, heating to increase the batteries temperature when the temperature is too low, and insulation to prevent sudden temperature variations in battery pack system. Here the temperature uniformity corresponds to minimizing the temperature difference on the battery cell surfaces and among each battery cell within a battery pack system. Namely, the lower the temperature discrepancy on the cell surface, the more the temperature homogeneity. BTMS strategies can be classified according to thermal strategies such as air cooling, direct refrigerant, secondary loop liquid cooling, phase change material (PCM), heat pipe, thermoelectric cooling, immersion technique, and integrated cooling systems including some of these strategies.

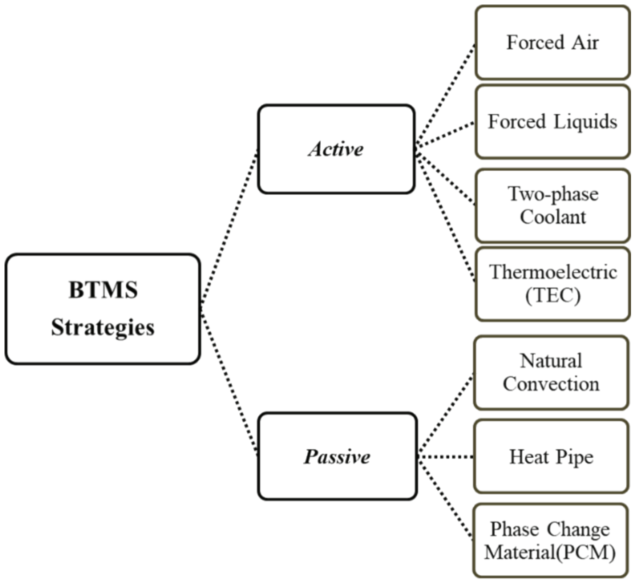

Figure 2. Active and passive battery thermal management strategies.

Figure 2 classifies the active and passive thermal management techniques according to energy consumption. Active BTMS techniques rely on the forced convection of the coolants in gas or liquid phases, while passive ones mainly include energy absorption materials such as phase change materials in order to remove the generated heat [53]. The performance of Li-ion batteries is significantly affected by the operating temperature. The lithium-ion batteries can be exposed power and capacity fade when the temperatures exceed approximately 40°C level. On the other hand, the low temperatures below -10°C can also cause reduced capacity and lithium plating [54]. Therefore, the thermal management strategies are essential, and a battery thermal management system should be carefully designed to keep Li-ion batteries in between the optimal temperature range of 15-35°C [55] in spite of the wide operating temperature range of -20°C to 60°C [56]. Furthermore, maximum temperature difference among the battery cells should be less than 5°C, and temperature discrepancy should be as possible as minimum [51]. In this way, safety risks and ageing of cells are eliminated; hence, lifetime and performance of the batteries are increased. Consequently, the importance of well-designed thermal management systems and cooling strategies is obvious for entire battery pack.

In spite of many alternative theoretical EV thermal management strategies are available (Figure 2), EV manufacturers dominantly prefer liquid-cooling strategy integrated with high conductive cold plates (Table 1). The reasons behind the selection of this technique are the thermal stability, low cost, simple applicability, and low irreversibility. In addition, it is obvious that EV manufacturers preferred air cooled BTMS technique especially for the relatively low-capacity battery packs as the specific heat and density

Table 1. Battery pack details for current electric vehicles ('s' and 'p' refers serial and parallel connections, respectively).

EV brand	Total Battery Capacity (kWh)	Battery Configuration	BTMS Strategy	Total Nominal Voltage (V)
Tesla Model X P100D	100	96s86p	Liquid cooling	350
Tesla Model S	100	96s74p	Liquid cooling	375
Jaguar I-Pace	90	108s4p	Liquid cooling	389
Mercedes EQC	80	96s4p	Liquid cooling	405
Porsche Taycan Turbo	79.2/93.4	198s2p	Liquid cooling	800
Audi e-Tron	71/95	108s3p/4p	Liquid cooling	396
KIA e-Soul	67.1	96s3p	Liquid cooling	375
Chevy Bolt - EV	66	96s3p	Liquid cooling	350
Hyundai Kona	64	98s3p	Liquid cooling	356
Tesla Model 3 SR	50	96s31p	Liquid cooling	350
Peugeot e-208	50	108s2p	Liquid cooling	400
Opel Corsa-e	50	108s2p	Liquid cooling	400
Hyundai Ioniq	40.4	88s2p	Liquid cooling	316.4
KIA e-NIRO	39.2	96s3p	Liquid cooling	240
BMW i3	33.7/42.2	96s1p	Liquid cooling	352
Honda e-Advance	35.2	96s2p	Liquid cooling	355.2
Renault Twingo ZE	22	96s2p	Liquid cooling	400
Nissan Leaf	39.4	96s2p/3p	Air cooling	360
Skoda CITIGO-e iV	36.8	84s2p	Air cooling	302.4
VW e-Golf	35.8	88s3p	Air cooling	323

> 70 kWh

40-70 kWh

< 40 kWh

of the air is comparatively low than liquid counterparts. On the other hand, thermal stability and uniformity in liquid BTMS satisfy the cooling requirements of many vehicles and it is well known in automotive industry as it is the choice also for internal combustion engines. Furthermore, liquid coolant can be mixed with some additives such as glycol, ethylene, high conductive nanoparticles etc. to enhance heat transfer performance and the temperature range which it can actively work. Besides, literature survey shows that many alternative integrated thermal management strategies are being developed and new solutions can be adopted by the automotive industry soon.

Note that post-lithium batteries may have different thermal and electrochemical characteristics. It is obvious that an important goal for the battery technology researchers is developing lower heat generation batteries while maintaining the battery stability. Next generation batteries may have better thermal characteristic due to newly developed (nanoparticle-based) materials. In addition, developed battery technologies will probably affect the battery thermal management methods and strategies. Nevertheless, the industry will go on utilizing the current battery thermal management strategies, but these strategies will be enhanced, and many optimization studies will be performed in parallel with the new battery technologies. Maybe, we will use nano-diamond batteries after ten years from now or we will develop high performance solids successfully absorbing to the generated heat and reform again. However, the thermal management systems are always going to contain conduction, convection and radiation-based heat transfer mechanisms and active-passive control techniques. This paper reviews the battery thermal management systems according to battery type, battery electro-chemistry and thermal management strategies. Experimental, theoretical, and numerical BTMS studies are classified and examined for the battery packs including cylindrical, pouch or prismatic battery cells. Proposed battery thermal management strategies are documented in a wide perspective having conventional techniques to innovative designs. Furthermore, post-lithium battery challenges for the metal-ion and the metal air batteries are reported in terms of battery chemistry, layer structures, and anode-cathode materials.

BTMS STRATEGIES BASED ON THE GEOMETRICAL FORM OF LITHIUM-ION BATTERIES

Prismatic Li-ion Battery Cells

Prismatic battery cells are rectangular prisms having many sublayers to obtain more energy density and capacity. Although the pouch cells are shaped as rectangular prisms and they are considered as prismatic cell in some of the literature papers, battery thickness of the pouch ones is very thin compared to prismatic cells. Many electric vehicle manufacturers such as BMW, Opel, Peugeot, Nissan etc. prefer prismatic type of batteries due to their high energy capacities. However, thermal management of the

EV battery pack including prismatic cells is more complex than cylindrical and pouch ones. Air-cooling strategy is the most common technique in the theoretical and numerical prismatic battery cell/pack investigations. Xu and He [57] performed numerical analysis for various airflow duct models such as horizontal, longitudinal and U-type. The main goal of their study was to improve the heat dissipation performance of a prismatic battery pack design. The results showed that longitudinal battery pack design provides more uniform temperature distribution in comparison with the horizontal one. On the other hand, longitudinal one did not satisfy the safety criteria; therefore, U-type BTMS design was also evaluated. They recommended double U-type duct design as the first choice for air-cooled BTMS. Similarly, Chen et al. [58] documented airflow distribution and thermal performance of a parallel flow BTMS by flow resistance network model and computational fluid dynamics (CFD) method (Figure 3a). The optimization processes are performed to reduce the maximum temperature and temperature difference values under 4C and 5C discharge conditions. They concluded that the temperature difference within the battery pack can be decreased up to 45% as the design is optimized. Peng et al. [59] analysed the air-cooling performance of prismatic battery pack having eight battery cells (Figure 3b). The simulation results were validated with experiments under 1C discharge condition. The findings indicated that cooling performance enhances when the inlet and outlet sections are located on the same side. Furthermore, Chen et al. [60, 61] optimized the space and flow configuration between the battery cells of several manifold models for air-cooled BTMS. Their objective was to minimize the maximum temperature of the pack and cells, and to obtain more uniform temperature distribution within the battery pack. The results indicate that temperature distribution can be achieved by the optimization of cell spacing and battery cell configurations, and the peak temperature values decrease as the temperature distribution becomes more homogeneous. Wang et al. [62] examined thermal and aerodynamic performance of a battery pack having 16 prismatic cells. Experimental tests are carried out in wind tunnel and the inlet temperature and velocity conditions are 21.6 ^{0}C and 8 m/s, respectively. The charge and discharge processes are performed at about 2.5C (1440 seconds) and it is documented that the resulting temperature is approximately 9 ^{0}C when charging.

Even if the air-cooled BTMS strategies have common usage in the literature, nowadays almost all EVs require liquid cooled BTMS techniques due to compactness and thermal stability. In addition, air-cooled BTMS dominantly depend on environmental conditions and the specific heat capacity and density of the air is very low in comparison to the liquid coolants. Xu et al. [63] documented the temperature distribution in EV battery pack for both without active cooling and with water based BTMS. Even if the nominal capacity of the prismatic Li-ion battery is 70 Ah, maximum cell temperature values of each active cooling scenarios are below 40 ^{0}C since the C-rate values are low ($\leq$ 1C). Jin et al. [64] experimentally observed the thermal performance of the mini-channel liquid cold plate (LCP) for two scenarios of straight plate and oblique finned (Figure 3c). The results showed that oblique fin structures with water-based LCP have superior performance. In contrast to that temperature uniformity index values of each case are compared, and the straight cold plate scenario was concluded as more homogeneous.

Panchal et al. [65] documented the water-cooled BTMS performance between 1C and 4C discharge conditions for 20 Ah prismatic battery cell. The experiments were performed with high conductive dual cold plates having nine inlets and outlets and ambient temperature is determined as a parametric value to observe the thermal performance of the BTMS at variant environmental conditions. Ten thermocouples are located on the battery surface and temperature contours for all the C-rate scenarios were documented in detail when the depth of charge value is 0, 0.5 and 1. The greatest temperatures are observed at the end of 4C discharge and 35 ^{0}C ambient temperature. In another battery thermal management paper of Panchal et al. [66], thermal performance of mini-channel based liquid BTMS strategy under 1C and 2C discharge conditions are examined. Likewise, Xu et al. [67] examined the thermal performance of a novel liquid and cold plate based BTMS for a prismatic battery module (Figure 3d). Since the nominal capacity of each prismatic battery cell is 60 Ah, they investigated the discharge operation at high ambient temperatures for heavy duty operations. The experiments were performed up to 40 ^{0}C and the temperature difference in the battery module is documented at about 3.7 ^{0}C. Huang et al. [68] documented the temperature distribution at battery surface for both straight and streamline shaped water-ethylene glycol channels. Effects of channel structures on the cooling plate performance are presented in detail and the results showed that the vascular type of streamline channels are more successful for both thermal management and pressure drop. Unlike these studies, iced plate and cold plate configurations with both air and liquid cooled BTMS strategies are documented by Darcovich et al. [69] under different performance characteristic. Two different drive cycle methods of US06 and HWY cycles were adopted for usage in electric vehicles. The cell temperature graphs for 50 km range are presented in detail for some BTMS cases and the results showed ice plate BTMS scenarios have thermally better performance for cooling and uniform temperature distribution. Chen et al. [70] performed an optimization study to observe the effects of the structural parameters on battery cooling performance. Some structural design variables such as width, thickness and gap of U-type liquid cooling channels were determined to obtain desired thermal performance. The response surface results of each test are documented to show the sensitivity of temperature and pressure values. The numerical results were compared with experiments, and it is concluded that the maximum

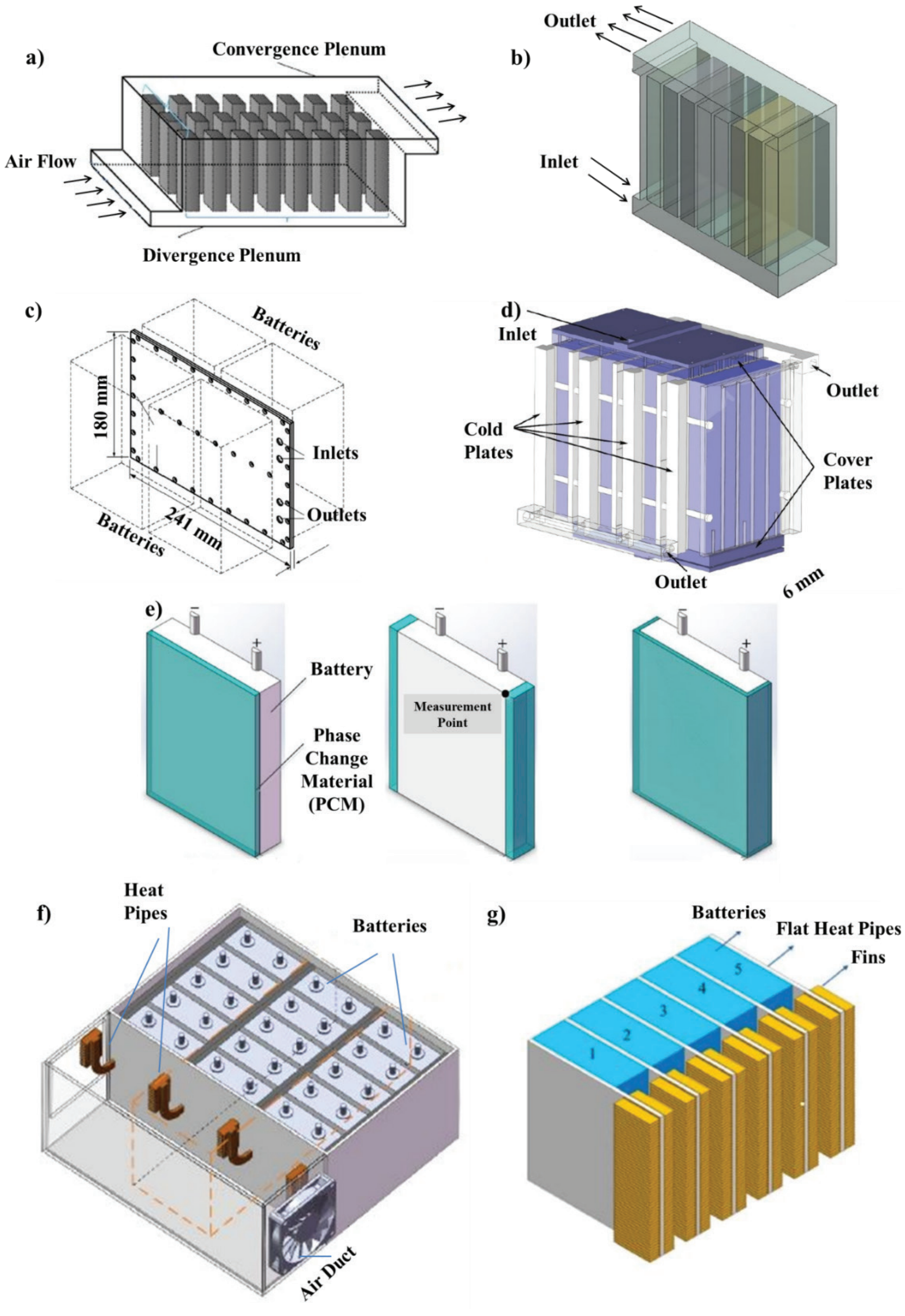

Figure 3. BTMS strategies for prismatic battery cell and pack, a-b) air-cooling [58, 59], c-d) liquid cooling [64, 67], e) PCM cooling [72], f) PCM-heat pipe integrated cooling [73], and g) heat pipe cooling [74].

temperature values of each method are very close to each other even if the maximum pressures are not.

On the other hand, PCM based BTMS techniques are also documented in the literature for EV battery cooling. Chen et al. [71] reviewed the effects of phase change materials and emphasized the main advantage of PCM based BTMS: efficient thermal control to limit the sudden temperature change. Wu et al. [72] experimentally and numerically observed the temperature distribution and temperature difference of a prismatic battery cell having PCM based BTMS (Figure 3e). Three-dimensional battery model was validated by experiments under 5C discharge conditions to obtain accurate heat generation values. Three different PCM configurations were analysed in detail; moreover, the effects of phase change material thickness and convection heat transfer coefficient value are documented. It is deducted that case where PCM fully covers the battery modules has better performance to prevent the temperature to rise beyond excess value. However, they also concluded that a multi-objective optimization study should be performed to decide the ideal PCM thickness since the thickness may affect temperature difference. In other work of Wu et al. [73], heat pipe assisted PCM technique given in Figure 3f was analysed and experiments for a prismatic battery module were performed under 1C-5C discharge conditions. The results of no cooling strategy, PCM based BTMS and heat pipe-PCM integrated BTMS were compared in terms of maximum temperature and temperature difference value. It is deducted that recommended BTMS strategy has significant cooling effect during battery charge/discharge cycles due to heat pipe reinforcement. Heat pipe aided BTMS technique experimentally tested by Zhang and Wei [74] for a prismatic battery module having five battery cells (Figure 3g). Rectangular fins were added to flat heat pipe tips to enhance the heat rejection from the batteries. The experiments and simulations were performed for discharge conditions up to 8C and the results showed that heat pipe-fin integration increases the temperature uniformity and thermal control. In another comprehensive study of Chen et al. [75], prismatic types of Li-ion battery cells were wrapped via PCM and heat pipe systems. They concluded that it is better to use PCM having lower melting temperature than the start temperature of heat pipe system to satisfy the thermal uniformity within the battery modules. On the other hand, Yue et al. [76] combined the heat pipe configuration with convective air and spray water techniques. In this integrated system, they aimed to reduce maximum temperature and increase the thermal uniformity within the investigated 75 Ah prismatic battery module. The findings indicated that maximum accessible temperature level within the battery module can be reduced up to %21 via proposed integrated cooling strategy.

Electric vehicle and energy storage industries extensively prefer prismatic Li-ion cells due to high energy storage capacity. Overheated regions are occurred through the centre of battery cells since the battery thicknesses of the prismatic Li-ion cells are comparatively high, and this thermal behaviour causes non-uniform temperature distribution. Surface-based cooling strategies are less effective than the pouch cells due to the thickness of the batteries. One alternative cooling strategy can be immersed cooling, in which the battery cells are kept in the liquid coolant medium. On the other hand, integration of tab cooling and surface cooling strategies increases the thermal uniformity. Because the tabs are manufactured by high conductive materials, conductive heat transfer mechanism-based cooling strategies contribute the battery thermal management. However, electrical isolation is a critical safety problem in tab cooling and immersed strategies since the current flows through the battery tabs.

Pouch Type Li-ion Cells

Pouch cells, which are more compact and quite thinner form of the prismatic batteries, have much more heat transfer surface area; therefore, thermal control and uniformity issues can be satisfied easier than prismatic ones. Thermal performance and characteristics of the Li-ion pouch cell are experimentally and numerically investigated in detail and many papers summarize thermal characteristics of them [77-79]. These studies are valuable to understand the temperature distribution on battery surfaces, peak temperature values at various C-rates, hot-spot regions occurring on pouch cell surfaces caused by non-uniformity on heat dissipation and heat generation [79, 80]. Even if these studies mainly focus on the thermal characteristics during discharge, Jaguemont et al. [81] examined the fast charging for two types of high-power Li-ion pouch cell and Mastali et al. [82] experimentally investigated the temperature rise under both charging and discharging conditions up to 5C. On the other hand, predicting the heat generation phenomenon is another key issue to design an adequate BTMS for EV battery pack. Neupane et al. [83] experimentally investigated the heat generation of the Li-ion pouch cell having 19.5Ah capacity. Heat generation rates were calculated at various C-rates and correlations which are function of state of charge and depth of discharge were documented for both charging and discharging conditions. The results showed that heat generation rate may reach up to 80W and it is always greater at discharge. On the other hand, Panchal et al. [84] examined the heat generation rate characteristics of a LiFePO4 pouch cell with active cooling. The experimental and numerical heat generation curves at various C-rates are compared in detail for thermal boundary conditions varying in the range of 5-35 ^{0}C. The simulation results are in agreement with experimental ones, and it is concluded that the greatest heat generation rate is obtained at 5^{0}C temperature and 4C discharge. Similarly, Schuster et al. [85] investigated the generated heating rate within a 40Ah Li-ion pouch cell for various current capacities. They used accelerating rate calorimeter method to calculate the heat generation, and it is documented that the generated heat energies are 11 kJ and 13 kJ at 1C charge and discharge, respectively. Xie et al. [86] used the heat generation model given in previous study [85] and observed heat generation phenomenon with another perspective. Two sub-models of current collector posts and battery cell parts are combined to obtain a 3D thermal pouch cell model. Even if many studies only focus on state of charge, current rate and temperature values were also taken into account in order to establish a more realistic heat generation model. 3D model results were also compared with experimental data for various C-rates, and it is documented that recommended model has better agreement with experimental results. Artificial neural network (ANN) approach was utilized to estimate the heat generation rate by Arora et al. [87]. Training data set based ANN model was validated with experiments at various ambient temperatures and C-rates. Coefficients of the correlation polynomials are shared in detail for a wide ambient temperature range of -10 ^{0}C to 50 ^{0}C under 0.33C, 1C and 3C discharge conditions. Battery tabs were exposed to high density current; thus, these high conductive parts of the battery cells are overheated regions. Samba et al. [88] examined the tab location effects on thermal behaviour of a Li-ion pouch cell. The thermal simulation results were compared for four distinct type of tab configuration. It was concluded that pouch cells with tabs located on opposite sides have more uniform temperature gradient. Likewise, Lee et al. [89] investigated the thermal behaviour of 55 Ah pouch cell with various tab location and aspect ratio configurations. They deduced that aspect ratio is dominant in heat generation uniformity, and it directly affects the temperature distribution. These studies contribute to the literature on understanding how heat generation and temperature distribution during charging/discharging occur; however, they do not propose a BTMS in order to satisfy thermal management for EV battery system.

Similar to prismatic battery cells, packs with pouch cells include air, liquid, PCM and heat pipe based BTMS strategies to eliminate hot-spot occurrence and thermal runaway. Although usage of the air as coolant is quite inefficient since it has low specific heat capacity, air manifolds have wide usage area in the literature due to ease of implementation. Park [90] analysed the cooling performance of five distinct air manifold designs without changing the layout or design of existing battery system. The battery pack including 72 pouch cells in two rows analysed in terms of thermal performance and pressure drop issues. He showed that type 5 with rectangular ventilation gap and tapered manifold design extending from 10 mm to 20 mm in the vertical direction effectively controls the temperature of battery pack system while decreasing the energy consumption over other types. Sun and Dixon [91] investigated the thermal behaviour of Li-ion pouch cells used in a hybrid electric vehicle and proposed some manifold models. Design of experiments (DOE) study was performed to evaluate the effect of cooling channel, duct type and corrugation on battery pack design. Inlet and outlet ducts with constant cross-sectional design were initially examined for a battery pack case that includes 80 Li-ion pouch cells. For this design, they documented that the temperature fluctuations may become up to 10°C. They concluded that the Z-type manifold decreases the fluctuation, and the best thermal performance is achieved with Z-type manifold model having conductive cooling plates. Wang et al. [92] documented thermal performance of Li-ion pouch cell with reciprocating air cooled BTMS experimentally. The temperature distributions at various depth of discharge (DOD) were captured by infrared imaging. They concluded that proposed reciprocating air-cooling strategy decreases the temperature difference on the battery surface. On the other hand, Li et al. [93] combined air cooling with silica cooling plate coupled by copper mesh structure (Figure 4a) in order to enhance the heat transfer. Temperature contours for battery module having five pouch cells were documented at distinct discharge times. Effects of silica cooling plate thickness, copper mesh region, air velocity, number of fans on thermal performance were investigated; consequently, optimal silica thickness and air velocity were documented.

On the other hand, a parametric optimization study [94] with design of experiments (DOE) and response surface methodology (RSM) aimed to achieve to enhance temperature distribution uniformity and to decrease peak temperature within air-cooled BTMS (Figure 4b). The results showed that temperature difference on battery cell and systems can be decreased up to 50 % with an accurate optimization approach. Akinlabi and Solyali [95] have recently reviewed the air cooled BTMS strategies and highlighted their advantages as their simplicity and low cost. Even if the pouch cells are more compact and have greater heat transfer surface area, their energy density is comparatively greater; therefore, alternative active cooling strategies were suggested and implemented for EV battery thermal control. Panchal et al. [96] experimentally investigated the heat flux from battery surface and temperature rise at various discharge conditions. They observed the battery temperature distribution for passive cooling of ambient air and active cooling with water-cold plate couple. Non-homogenous temperature distributions were captured via thermal camera, and the results showed that peak temperature regions occur through high conductive collectors. On the other hand, Gungor et al. [97] focused on the ethylene-glycol-water based liquid-cooling system satisfying the optimal operating temperature range of pouch type Li-ion battery module. In this study, we mainly aimed improving the thermal performance while considering the energy consumption of the proposed system.

Patil et al. [98] used water as BTMS coolant and they focused on U-type microchannel cold plates presented in Figure 4c. Heat generation rates at varying C-rates were experimentally documented, and then BTMS simulations were carried out with numerical model. The analyses were performed at various Reynolds numbers and temperature difference on pouch cell surface. Peak temperature difference can reach up to 20 ^{0}C as the coolant distribution

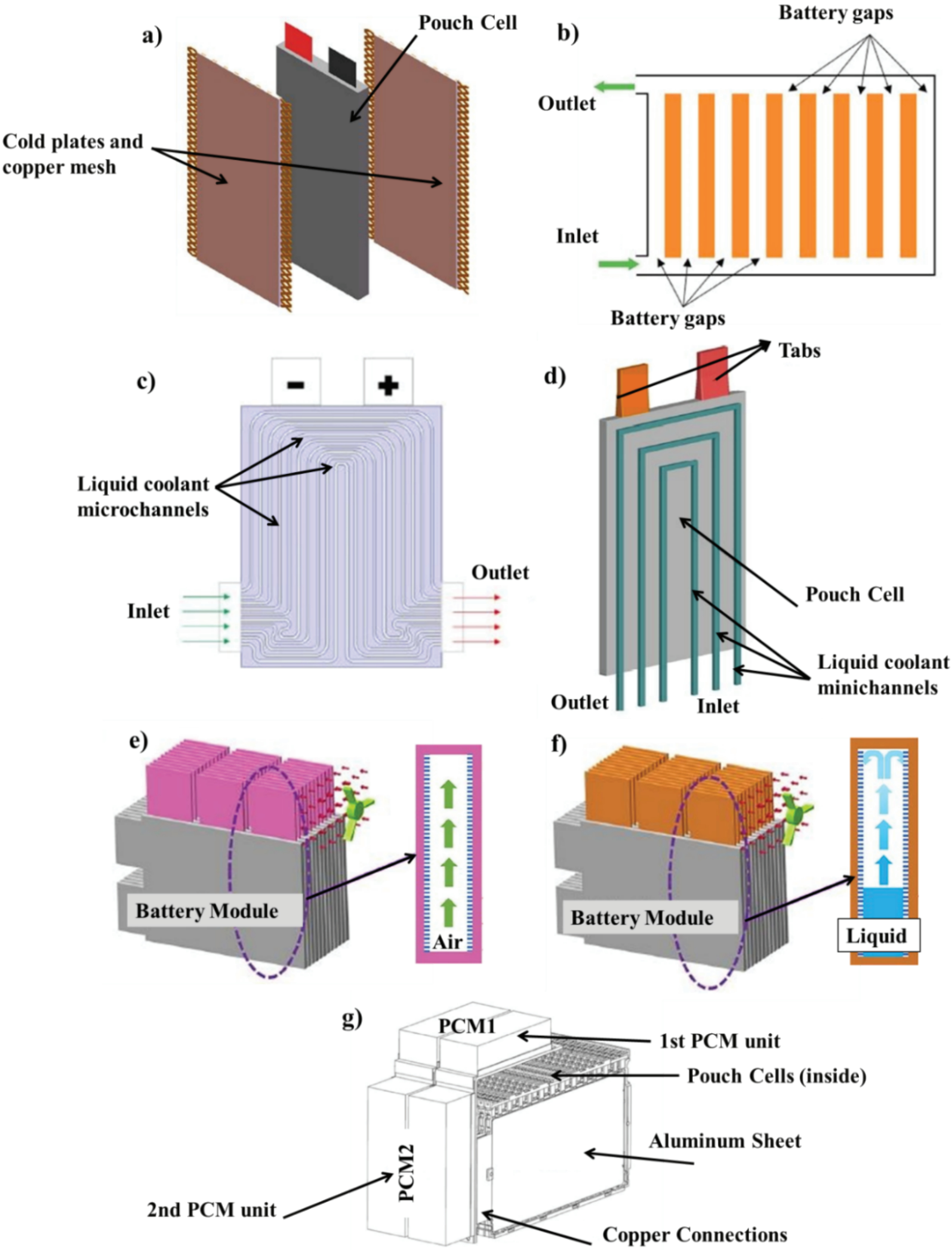

Figure 4. BTMS strategies for pouch type battery cell and pack, a-b) air-cooling [93, 94], c-d) liquid cooling [97, 98], e-f) heat pipe cooling [102] and g) PCM cooling [106].

causes thermal non-uniformity. Likewise, Li et al. [99] investigated the temperature distributions of pouch cell and battery pack with U-type mini-channel-cold plate BTMS (Figure 4d). They examined the effects of inlet velocity and discharge rate in order to prevent thermal runaway risks. The results showed that cold plate contributes to reduce the maximum. Furthermore, Chung and Kim [100] compared the thermal performance of distinct BTMS designs for electric vehicle battery pack having 144 pouch cells in total. The battery pack divided some stack scenarios for best cooling, and they focused on decreasing the inner-cell and inter-cell temperature differences. On the other hand, Gocmen et al. [101] have recently examined the thermal performance of various air manifold designs. Battery module having 15 pouch cells was developed to obtain a manifold design which satisfies uniform flow distribution between the battery cells and homogeneous temperature distribution within the manifold. The results showed that flow distribution variance among the batteries can be decreased below 1% with step-constructal type manifold design.

Heat pipe and PCM based BTMS strategies are also commonly investigated for large capacity pouch cells. Mo et al. [102] compared air-cooling, micro heat pipe-air and micro heat pipe-liquid based BTMS strategies in terms of peak temperature values and thermal uniformity. The BTMS strategy for heat pipe-air and heat pipe-liquid cooling are shown in Figure 4e-f, respectively. It is concluded that air-cooled scenario shows great temperature difference while micro heat pipe and liquid combination achieves thermal homogeneity whose temperature difference is below 5 ^{0}C. Similarly, Zhao et al. [103] documented the thermal experiment results for heat pipe based BTMS. They compared the performance of heat pipe-natural convection, heat pipe-air cooling and heat pipe-wet cooling scenarios of low-capacity pouch cell designs. It is deduced that, heat pipe with water spray effectively controls the temperature rise of the batteries and this BTMS design keeps the temperature within appropriate range. Oh et al. [104] numerically investigated the effects of various phase change materials on battery thermal management. Thermophysical properties of each type of PCM are shared in detail, and the results showed that maximum battery surface temperature can be reduced up to 7 ^{0}C. In the second part of the study, Kim et al. [105] experimentally observed the temperature characteristic of various PCM strategies. The experimental results are compatible with previous study [104] in terms of temperature rise between without PCM and other PCM techniques. They also recommend PCM based BTMS to increase the lifetime of the batteries. Xie et al. [106] performed numerical and experimental analyses with PCM cooling (Figure 4g) under both charging and discharging conditions. Numerical model was validated by experiments, and effects of air flow rate and PCM liquid fraction were investigated in terms of thermal control. They concluded that air-PCM integrated cooling strategy has effective thermal management ability according to simple air cooling.

Compared to the cylindrical and prismatic battery packs, pouch cells have large heat transfer surface area. Furthermore, temperature distribution and maximum temperature levels are different than the cylindrical ones. Many numerical and experimental studies showed that regions close to the tab locations have higher temperatures in pouch and prismatic Li-ion cells. This thermal phenomenon gives us a clue for strict cooling design and homogenous battery thermal control. The coolant inlet can be located close to the tab locations, and heat can initially be absorbed from the overheated regions. In this way, battery thermal management systems both satisfy cooling demand and temperature homogeneity issue. It is obvious that thermal safety and uniformity in pouch battery packs can be achieved via liquid cooling and high conductive cooling plate integrations. Yet, if the thermal management method is air cooling, it is recommended to add some fin structures on battery surfaces. Extended fin structures increase the effectiveness of the air cooling, and this approach gives a compact thermal management solution.

Cylindrical Cells in Various Dimensions

Cylindrical battery cells are the most generally used type of storage device for the primary batteries. The battery layers are wrapped around an axis to obtain a cylindrical compact form. Today, EV industry utilizes from 1865, 2170, and 4680 types of cylindrical Li-ion battery cells having distinct energy densities. The cooling medium is also essential for the cylindrical type of battery cells because it affects ease of use, cost, maintenance, life, and efficiency for a battery thermal management system [107]. Air-based thermal management systems have been used due to the low cost and ease of adaptability in many energy storage applications. However, there are some challenges to make them more efficient and compact [108, 109] because of the thermal properties of air (low thermal conductivity and specific heat), energy consumption for cooling, geometry of cylindrical batteries and spacing among them [110, 111]. Generally, the batteries are in direct contact with air for cooling. The air cooled BTMS can be use parallel cooling or series cooling methods. However, the parallel cooling method is rarely used to cool battery packs including cylindrical cells, because of complexity and difficult integration of plenums. Instead, the coolant is driven into the battery pack by fans and flow over the battery cells as series through the pack. Thus, heat is transferred from the cells to the working fluid. However, the homogeneous temperature distribution in the pack cannot be achieved until the optimum battery cell arrangement and airflow configuration are uncovered.

Varying coolant flow rates and flow paths, positions of inlet/outlet sections of air, spacing between the batteries and layout of the cylindrical batteries are common investigation objectives to enhance heat transfer removal from the cylindrical battery cells [112–114]. Jiaqiang et al. [115] investigated different air cooling strategies including

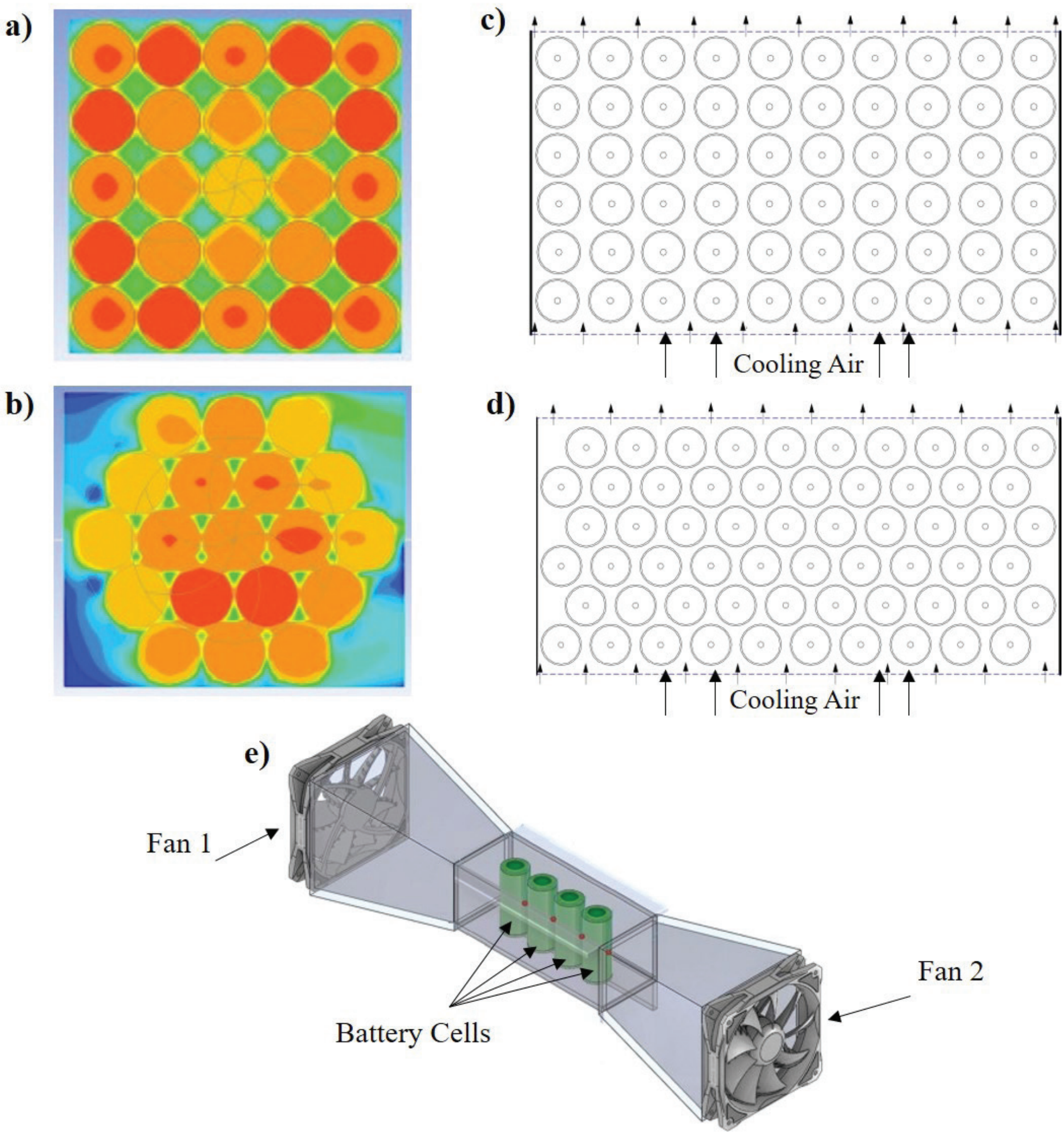

Figure 5. (a-b) The cubic and hexagonal structure when the fan is positioned at the top of module [116], c-d) the aligned and staggered cell layouts [117], e) the battery module cooling with the active control using reciprocating air flow [118].

various inlet and outlet configurations of air for a battery pack consisted of 60 cylindrical cells. The results show that the lateral located inlet and outlet regions at different sides perform more effective than the same side configuration. Wang et al. [116] examined the thermal performance of battery modules which have several fan locations and cylindrical battery cell arrays including 1×24, 3×8 and 5×5 rectangle arrays, 19 cells hexagonal arrays, and 28 cells circular arrays. They uncovered that the cubic (5×5 rectangular) arrangement in Figure 5a provides the best cooling capability when the fan is positioned at the top of the module. In addition, the hexagonal structure is described as the best option considering space utilization as shown in Figure 5b. Yang et al. [117] conducted comparative analyses to investigate the effects of transverse and longitudinal spacings on the cooling performance for the staggered and aligned cylindrical battery cell layouts as shown in Figures 5c and 5d, respectively. The study shows that the temperature rise on the cells increases as longitudinal and transverse intervals increase for staggered arrays. However, optimization of the longitudinal spacing reduces temperature rise for aligned battery arrangement. They stated that the alignment arrangement should be selected with consideration of thermal management as it affects temperature uniformity greatly. On the other hand, He et al. [118] studied battery module cooling with active thermal control using reciprocating air flow which is generated by two fans placed at inlet and outlet of the tunnel. In the Figure 5e, the cylindrical type 26650 lithium-ion battery cells which have capacity of 2.6Ah were aligned in a row in the tunnel and only their lateral external surfaces are in contact with airflow. The study shows that the case using active control and reciprocating flow reduces the parasitic power consumption up to 84%. However, the temperature rise on the cells slightly increases as 0.5°C compared to the case using no active control. Similarly, Mahamud et al. [119] performed two-dimensional CFD simulations in order to cool the battery pack which has aligned cylindrical battery configuration using reciprocating air flow. They aimed to increase temperature uniformity with their cooling system that reverses the airflow periodically. The results show that the reciprocating airflow reduces temperature difference between the battery cells by approximately 4°C and the maximum cell temperature by 1.5°C.

Air-based BTMS may remain incapable to provide adequate cooling for the cylindrical type of battery packs at higher C-rates, with higher number of cells or under extreme environmental conditions due to the low conductivity and density of the air. The air has lower heat capacity compared to the coolants used for liquid-cooling such as water, water-glycol mixture, oil or equivalent liquid mixture. However, liquid BTMS also have disadvantages such as leakage potential, even if they are more efficient and compact than the air-based systems. Liquid-based BTMS for battery packs with cylindrical cells have different strategies such as direct or indirect cooling. Direct cooling can be considered as much better than indirect cooling in terms of high heat transfer rate, simplicity, packaging density and cost. However, direct cooling of the batteries has several drawbacks such as electrical short circuit, corrosion and increment in weight as all the systems submerged in liquid. Moreover, it is not preferred usually in electric vehicle applications from the practical aspects of systems [120]. Nevertheless, the strategy has been used other application areas for battery thermal management [121–123] due to superiority on heat transfer performance [124, 125]. On the other hand, indirect cooling with tubes, cold plates with integrated channels and fins, and jacket cooling strategies are commonly used by the electric vehicle manufacturers, although the thermal resistance of the indirect cooling strategy reduces the heat transfer rate compared to the direct liquid cooling. Liquid cold plate cooling is the most preferred option in battery packs including pouch and prismatic cells, but this technique becomes more difficult to apply in cylindrical cells due to inconsistency between cell geometry. The indirect cooling strategy is distinguished as suitable method for most of the practical application. EV manufacturer Tesla developed a curvy channel structure (Figure 6a) around the cylindrical battery stacks to cool battery pack of Model S [126, 127]. The water-glycol mixture runs as coolant in the curvy channels which have radius of nearly equivalent the outside radius of the cells. The coolant contacts partially and passes through the cells as series. This situation seems not much efficient; however, it is a good solution in terms of safety, manufacturability, and practicality for EVs. Zhao et al. [128] studied the performance of the wavy channels around the cylindrical cells. They investigated the effects of C-rate, coolant flow rate, interface between neighbouring batteries, battery and the channel outer wall as shown in Figure 6b. The results show that the maximum temperature and temperature uniformity can be kept below 35°C and 1°C, respectively by the wavy channel cooling (with 0.5m/s inflow velocity, 25°C inflow temperature and 5C discharge/charge rate).

Basu et al. [129] documented indirect liquid coolant strategy for the cylindrical battery pack thermal management system. They used aluminium conduction elements surround the cells between the aluminium channels carrying liquid coolant in order to transfer generated heat by thermal conduction. The study shows that the maximum temperature rise can be kept around 7K for 2.7C discharge rate and 0.01 m/s coolant inlet velocity. Although the studies reviewed above claim to provide the adequate cooling with partially surface contact, the thermal efficiency can be improved due to increasing heat transfer interface area. Thus, the cooling strategy having increased contact surface area can be defined more efficient in terms of thermal management. Therefore, another option is the placing cylindrical battery cells in the housings or similar structures of the module, and the coolant liquid passes through external surface of these structures. In this way, the coolant leakage and electrical short are prevented while the thermal efficiency and temperature uniformity are increased. However, these additional structures cause total weight of the battery pack to increase. Zhao et al. [130] numerically investigated the effects of number of channels, mass flow rate, flow direction and entrance size of proposed cooling method (mini channel liquid cooled cylinder, (LCC)) on the heat dissipation for cylindrical battery cells. Figure 6c shows the schematic of LCCs including 40 battery cells. The results of simulations show that if the number of channels is (minimum) 4 and the inlet mass flow rate is 10^{-3} kg/s, the maximum temperature can be kept below 40°C although decreasing the temperature difference between the positive and negative poles is difficult in the LCC. In addition, the proposed cooling method with LCC can be defined as favourable as natural convection cooling only when the number of channels is more than eight. Rao et al. [131] investigated the

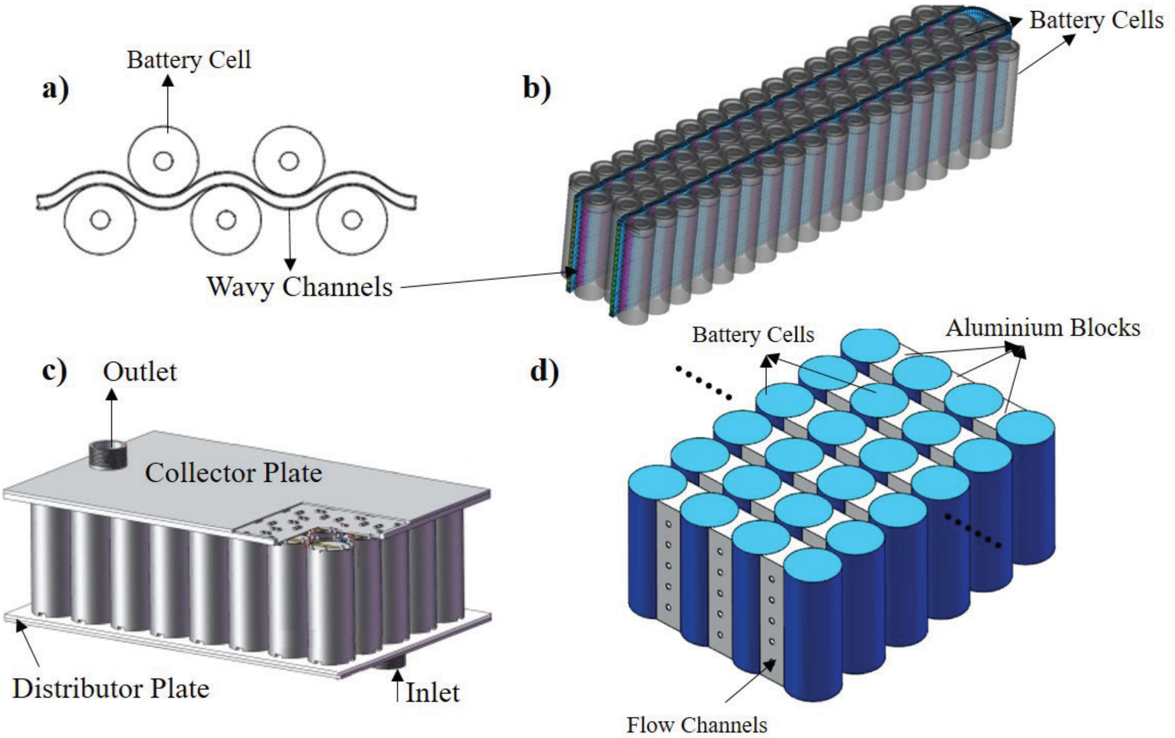

Figure 6. (a) The schematic of wavy channel [126] (b) The schematic of the battery pack using wavy channels [128], c) the schematic of LCCs including 40 battery cells [130], d) the schematic of battery pack using cooling blocks with liquid channels [131].

performance of BTMS with various contact area along the flow direction. Each aluminium block between the battery cells has five cooling channels shown in Figure 6d. The heat conducted to blocks is transferred to coolant by the convection heat transfer mechanism. The results show that the varying contact area cases provide better performance in terms of increasing temperature uniformity and decreasing maximum temperature and weight of battery module compared to constant contact area case.

Air and liquid cooling strategies are commonly complex, bulky, and need power-requiring components such as fans and pumps. On the other hand, PCM cooling strategy transfers the heat from the batteries by utilizing the latent heat of phase changing without using any additional components or systems. Compared to the active cooling methods, passive cooling methods such as PCM-based cooling are paid attention due to their potential on thermal simplicity, low-cost, effective heat transfer [132]. However, there are also some drawbacks such as low thermal conductivity and volume changing during phase change. Therefore, addition of high conductive materials such as carbon fibres, carbon nanotubes, graphene, metallic foam and metal particles is considered to improve the overall thermal performance [133]. In the literature, one of the most popular and common investigation subject is the PCM-based cooling for BTMS applications [134–136]. Cylindrical cells have the most common PCM applications and investigations [137-140] since their outer surface are not flat and forcing the coolant towards its surfaces is more complicated than the prismatic and pouch cell. Initially, Al-Hallaj and Selman [141] proposed and patented BTMS based on PCM. They integrated the PCM within the battery module as shown in Figure 7a. The results show that the temperature levels of the PCM integrated battery module in whole scenarios are lower than the module without PCM strategy. In addition, the stored latent heat may keep the battery module at a higher temperature than surrounding temperature and this situation provides better performance under cold weather conditions for battery pack. Sabbah et al. [142] compared the effectiveness of the active air cooling and passive PCM cooling methods. The results of simulations show that the PCM based passive cooling is more efficient than forced air cooling. However, the conventional application method which is the filling whole free spaces with PCM causes to increase the temperature difference between centre and corner battery cells due to non-uniform heat rejection to the ambient air. Jilte et al. [143] suggested a battery layout to provide better heat dissipation and temperature uniformity. In the proposed arrangement, each module consists of six cylindrical battery cells that is placed in cylindrical housing filled with PCM. The cylindrical housings are also interconnected to each other in order to increase the heat transfer by

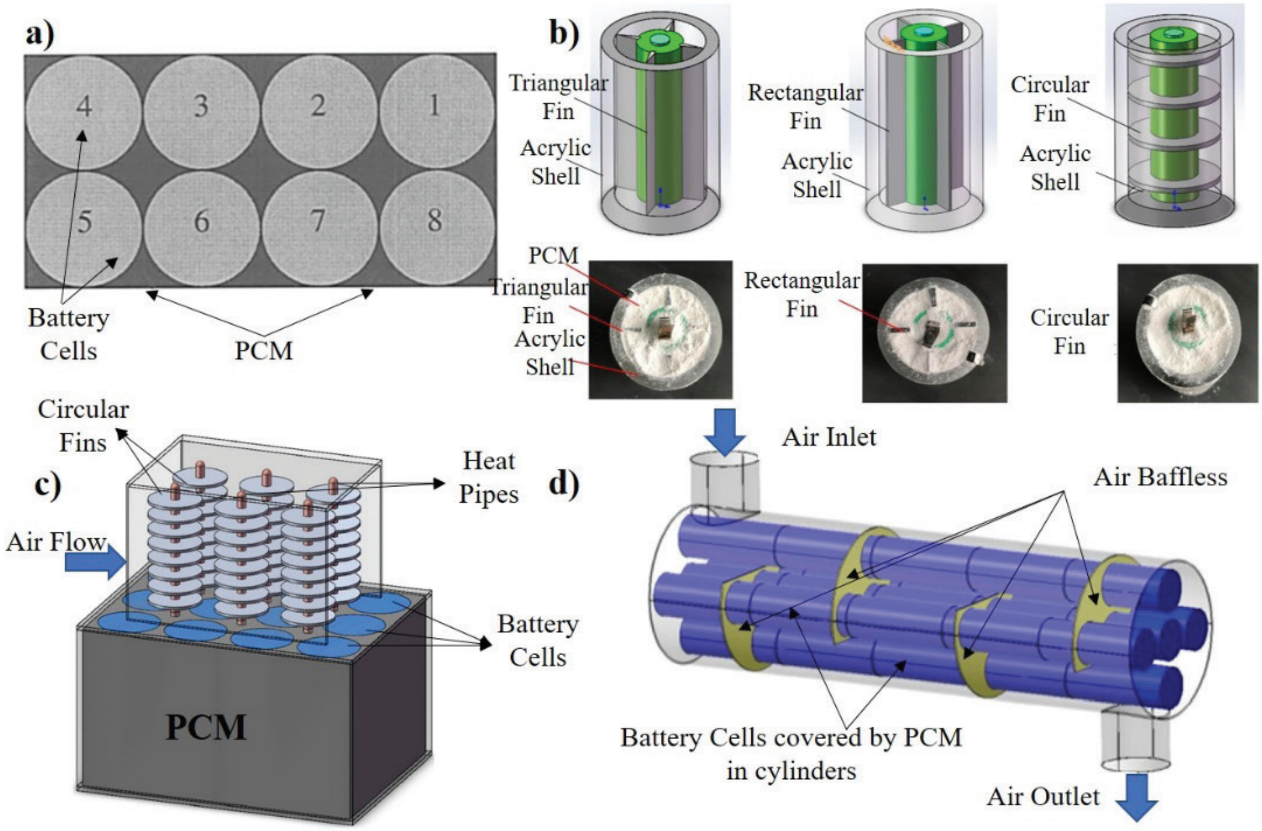

Figure 7. (a) The proposed PCM-based cooling EV module [141] (b) Three different fin cases and corresponding experimental images [148], c) PCM/finned-HP integrated thermal management module [149], d) the PCM integrated shell and tube battery pack [150].

natural convection. Proposed BTMS provided temperature uniformity within 0.12°C and reduces the weight of battery pack. In the literature, the BTMSs based on pure PCM have enhanced using highly conductive additives. Similarly, thermal performance of a nano-enhanced PCM application was investigated for cylindrical Li-ion battery cell in a recent study of Jilte et al. [144]. Evolution of experimental and numerical melting forms were documented in detail. Trans-radial PCM arrangement was proposed for more effective thermal management of the investigated Li-ion battery cell.

Zhang et al. [145] examined various mass fractions (0%, 5%, 10%, 15%, 20%, 25%) of aluminium nitride (ALN) to add composite PCMs and analysed the effects of AlN additives. The results show that the fraction of 20% provides the maximum enhancement in terms of thermal properties. In addition, AlN based composite PCMs-cooled battery module reduces the maximum temperature by 19.4% compared to air-cooled module. PCM saturated with metal foam is also another thermal conductivity enhancement method that is commonly employed for the passive cooling. Abid Hussain et al. [146] studied graphene coated nickel (GcN) foam saturated with PCM to increase thermal conductivity of pure paraffin. The results indicate that the thermal conductivity was increased by 23 times. Similarly, Samimi et al. [147] numerically studied the thermal performance of lithium-ion battery cell embedded into PCM/carbon fibre composite and validated the results with experimental data. The study shows that the higher concentration of carbon fibre in the PCM increases the uniformity of temperature distribution, and the average thermal conductivity enhancement is about 105% with that technique. Weng et al. [148] placed the fins into PCM and investigated the effects of the fin three different fin shapes (Figure 7b) on PCM based cooling module to solve the issue of low thermal conductivity. They documented that the longitudinal fins provide better heat dissipation by natural convection compared to the others. In addition, when the air convection coefficient is increased, the heat dissipation performance of the circular fins is also increased due to their larger surface area. Besides, the combination of active and passive cooling can be considered more effective technique for the PCM based BTMSs. For example, Zhao et al. [149] examined the thermal performance of PCMs/heat pipe coupled BTMS for cylindrical batteries. They divided the experiments into three parts (no PCM, filled with PCM and PCM/HP coupled module) and compared the performance of each one. Figure 7c shows the coupled model schematic which consists of 12 cells, PCM and heat pipes-cylinder fins structure. The study demonstrates that the coupled BTMS reveals better performance than the other systems in terms of controlling the maximum temperature rise (below 50°C). The coupled module reduced the maximum temperature difference in the battery by 62.5% and keeps the temperature variations below 5°C. Furthermore, Jiang et al. [150] proposed tube-shell battery pack integrated with PCM coupled with air cooling system as shown in Figure 7d. Each aluminium tube mounted on the baffles is wrapped with extended graphite/paraffin composite and includes the five cylindrical battery cells connected as series. The results show that the surface temperature of batteries and the maximum temperature difference across the battery are kept in the PCM melting range of 41–44°C and within 1–2 °C, respectively. Note that more detailed information about the phase change materials and their possible applications on BTMS techniques have recently reviewed by Luo et al. [151].

Battery module and battery pack configurations are not similar for the cylindrical batteries and pouch-prismatic ones. These configurations directly affect temperature distribution and maximum temperature of the battery cell and battery pack. In cylindrical cells and even battery packs, the centreline circumference of each battery cell overheats under both charge and discharge conditions. Since cylindrical battery packs have less heat transfer surface due to large gaps between the cells and cells behaves as a block radial direction, PCM based thermal management strategy may be effective cooling method. On the other hand, air cooling strategies can be particularly efficient when the air is affected from the upper and lower sides of the cylindrical battery pack. Nevertheless, air flow rate should be comparatively high to reduce the temperature level. In addition, liquid cooled thermal management is only preferred method in cylindrical battery-based EV industry. Tesla Inc. uses liquid cooled (propylene glycol or anti-freeze) serpentine designs with various loop configurations to enhance the thermal uniformity.

POST-LITHIUM BATTERIES

Batteries should have great energy density, light weight, high recyclability, long life cycle and thermally stable operations as they are requirements in many advanced applications such as EVs. Therefore, post lithium battery concept has emerged to satisfy the requirements and future expectations [152, 153]. Walter et al. [154] have recently investigated some post lithium battery alternatives to overcome some disadvantages of Li-ion batteries. They examined sodium-ion, magnesium-ion, aluminium-ion, sodium-magnesium dual-ion and aluminium-graphite dual-ion battery chemistry in detail. It is emphasized that these energy storage alternatives still need optimization studies to implementation in field whereas their cost is comparatively lower than Li-ion batteries. Ponrouch and Palacin [155] discussed the post lithium battery chemistries and compared them with current Li-ion battery technology. They documented that instability on lithium manufacturers and rise in the lithium costs ensured to research new energy storage chemistry alternatives such as metal-ion or metal-air batteries. Even if the metal-air batteries have known and used before [156-159], especially lithium-air (Li-air) battery chemistry may enable higher energy density than Li-ion batteries. In Li-air or Li-oxygen type of post lithium chemistry, air side is used as cathode material; however, thermal stability issue needs to overcome. Furthermore, Chang et al. [160] proposed lithium-bromide (Li-Br) based rechargeable battery and defined that type of battery as having more energy density than Li-ion and being more stable than Li-air batteries. Lithium-sulphur (Li-S) is another post lithium alternative since sulphur has high theoretical energy capacity, and it is abundant in nature [161].

On the other hand, some papers mainly focused on nanostructure characteristics of battery electrodes [162-164] to improve electrochemical and thermophysical properties of post lithium batteries. Wang et al. [164] discussed and evaluated many post lithium chemistry alternatives with nanostructure media. The superiority and shortcomings of the post lithium batteries are shared, and they also concluded to commercialization obstacle of some novel post lithium battery chemistries. Manzhos [165] focused on organic electrode materials and Ma et al. [166] proposed some binder choices to obtain more powerful and stable post-lithium batteries. Likewise, Ahmad et al. [167] evaluated the carbon-based materials as a candidate of the cathode material for the post-lithium batteries. On the other hand, Wu et al. [168] used de-alloying technique to create nanoporous structures for metal electrodes of sodium, magnesium, aluminium, zinc and potassium. They concluded that the nanostructures may enhance the charge transfer and electrolyte percolation within post-lithium battery chemistry. Shi et al. [169] documented the recent advances on nanofiber-based electrode layers of the investigated post-lithium batteries. Chemistry, morphology, and nanofiber structure were determined as the main parameters affecting the post-lithium battery performance. Note that thermal management and heat generation characteristics of the post-lithium battery technologies are still in research, and this is a new challenge for the electric vehicle industry. Even if the R&D processes are in progress, the literature highlights that the shortcomings on electrochemical and thermal stabilization are main obstacles for the commercialization of post-lithium battery technologies.

CONCLUSION

Li-ion and post lithium battery technologies enhance parallel with energy storage demand and battery industry gradually enables higher energy density, permanent capacity, and longer lifetime. Electric vehicle technologies are contributed to improvements in battery technologies since end users desire to have electric vehicles having fast charging and long-range abilities. However, there are two inevitable and critical situations against the high-performance battery technologies: overheating and thermal runaway. At this point, thermal control systems called as the battery thermal management systems (BTMS) have emerged to eliminate the overheating and safety risks causing in various lithium-based and post-lithium EV battery systems. BTMS should satisfy homogenous temperature distribution and thermal control to keep the peak temperature level under the critical temperatures. Otherwise, battery capacity and EV performance reduce, capacity fade increases and safety risks such as fire, explosion and harmful gas emissions emerge. In this review, various BTMS strategies are reviewed in detail and compared in terms of battery geometry, thermal control strategy, coolant type and maximum temperature level for Li-ion and post-lithium batteries.

In the near future, the transition from fossil fuel to electric vehicles will accelerate as the obstacles to battery capacity, charging speed, thermal efficiency of anode and cathode materials, weight, volume, and cost are eliminated. However, these advances in electric vehicle technology will bring with it bigger challenges to overcome in terms of thermal control and safety. At this point, innovative and efficient thermal management strategies will be needed beyond the mentioned thermal control designs although they seem providing adequate cooling for now. It can be concluded that the next generation battery packs with developed cell chemistry and design will consist of battery packs hybridizing several active and passive heat transfer mechanisms rather than including them solely.

NOMENCLATURE

C	C-rate
I	Circuit current, A
$\dot{q}$	Heat generation rate, W
T	Temperature, ^{o}C
V	Voltage, V

Subscripts

c	Battery cell
o	Open circuit

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AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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