Applied Thermal Engineering 149 (2019) 192–212

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Review on battery thermal management system for electric vehicles

Jaewan Kim, Jinwoo Oh, Hoseong Lee*

Department of Mechanical Engineering, Korea University, 409 Innovation Hall Bldg., Anam-Dong, Sungbuk-Gu, Seoul, Republic of Korea

HIGHLIGHTS

- The heat generation phenomena and thermal issues of Li-ion battery are introduced.
- The various BTMSs of EVs are reviewed according to the thermal cycle options.
- The advantages and disadvantages of various BTMSs are discussed.
- A novel BTMS is proposed for the next generation Li-ion BTMS.

ARTICLE INFO

Keywords:
Battery thermal management
Lithium-ion battery
Vapor compression cycle
Next generation battery

ABSTRACT

The lithium-ion batteries are widely used for electric vehicles due to high energy density and long cycle life. Since the performance and life of lithium-ion batteries are very sensitive to temperature, it is important to maintain the proper temperature range. In this context, an effective battery thermal management system solution is discussed in this paper. This paper reviews the heat generation phenomena and critical thermal issues of lithium-ion batteries. Then various battery thermal management system studies are comprehensively reviewed and categorized according to thermal cycle options. The battery thermal management system with a vapor compression cycle includes cabin air cooling, second-loop liquid cooling and direct refrigerant two-phase cooling. The battery thermal management system without vapor compression cycle includes phase change material cooling, heat pipe cooling and thermoelectric element cooling. Each battery thermal management system is reviewed in terms of the maximum temperature and maximum temperature difference of the batteries and an effective BTMS that complements the disadvantages of each system is discussed. Lastly, a novel battery thermal management system is proposed to provide an effective thermal management solution for the high energy density lithium-ion batteries.

1. Introduction

Interest on electric vehicles (EVs) including hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) has significantly increased, as environmental regulations on greenhouse gas (GHG) emission have been strengthened [1-3]. The fundamental challenge for EVs is to find an appropriate energy storage system that can support high mileage, fast charging and high-performance driving [4-6]. Recently, rechargeable lithium-ion (Li-ion) batteries are regarded as the most suitable energy storage device for EVs because of their higher energy density, higher specific power, lighter weight, lower self-discharge rates, higher recyclability and longer cycle life than other rechargeable batteries such as lead-acid, nickel–cadmium (Ni-Cd), nickel-metal hydride (Ni-MH) batteries [7-9]. They also have the advantage of no memory effect [10,11]. However, the performance, life and safety of these Li-ion batteries are very sensitive to temperature [12]. It is difficult to develop a coherent and comprehensive mechanism that degrades the performance and safety of Li-ion batteries due to a large number of electrode materials and electrolyte mixtures used in commercial batteries. Nevertheless, it is clear that the performance and stability of Li-ion batteries are reduced at the abnormal temperature range for nearly all cell materials. The temperature change of batteries is usually inevitable because they are affected by environmental conditions and release heat by a series of chemical reactions during charging and discharging [13]. Therefore, an efficient battery thermal management system (BTMS) is required to maintain the proper temperature range and to minimize the temperature gradient of these batteries to prevent adverse effects from temperature [14]. Pesaran (2002) and Pesaran et al. (2013) suggested that the operating temperature range should be kept between 15 °C and

* Corresponding author.
E-mail address: hslee1@korea.ac.kr (H. Lee).

https://doi.org/10.1016/j.applthermaleng.2018.12.020
Received 11 September 2018; Received in revised form 14 November 2018; Accepted 3 December 2018
Available online 04 December 2018
1359-4311/

Nomenclature

Abbreviations

AC	air conditioning
BEV	battery electric vehicle
BTM	battery thermal management
BTMS	battery thermal management system
CFD	computational fluid dynamics
COP	coefficient of performance
DC	direct current
DOD	depth of discharge
EG	expanded graphite
EV	electric vehicle
FCEV	fuel cell electric vehicle
GHG	greenhouse gas
HPTMS	heat pipe heat management system
HEV	hybrid electric vehicle
LDPE	low density polyethylene
NEDC	new European drive cycle
Ni-Cd	nickel-cadmium
Ni-MH	nickel-metal hydride
Li-ion	lithium-ion
OHP	oscillating heat pipe
PCM	phase change material
PEMFC	proton exchange membrane fuel cell
PHEV	plug-in hybrid electric vehicle
SLCP	silica-liquid cooling plate
SOC	state of charge
TEC	thermoelectric element cooler
UMHP	ultra-thin micro heat pipe
VCC	vapor compression cycle

Symbols

I	volumetric current, A/cm^3
$\dot{Q}$	heat generation rate, J/cm^2•s
T	absolute temperature of the cell system, K
$T_{inletair}$	inlet air temperature, °C
T_{max}	maximum temperature, °C
ΔT_{max}	maximum temperature difference, °C
$T_{inletliquid}$	inlet liquid temperature, °C
T_{σ}	temperature uniformity, °C
U	open circuit voltage, V
V	applied voltage, V
V_{liquid}	liquid velocity, m•s^{-1}
T_{amb}	ambient temperature, °C
T_{avg}	average temperature, °C

35 °C and the maximum temperature difference (ΔT_{max}) from module to module should be below 5 °C to avoid adverse effects of Li-ion batteries [15,16]. The energy density of Li-ion batteries surpasses all previous competing batteries, but nevertheless, today's EVs are demanded to use higher energy density batteries than ever before and to accumulate more cells in the pack to increase the mileage. This trend further increases the internal heat generation and heat accumulation of the batteries, thereby increasing the importance of the BTMS.

There were several review papers on BTMS in the past. Rao and Wang (2011) firstly reviewed the overall thermal energy management of BEVs, HEVs and fuel cell electric vehicles (FCEVs) [18]. They investigated the development of power batteries and the mathematical models of battery thermal behavior that is fundamental to the proper design of BTMS. Then they briefly reviewed and classified BTMS according to the heat transfer mediums: air, liquid and phase change material (PCM). Especially, they focused on BTMS using PCM and investigated the thermo-mechanical behaviors and heat transfer enhancement of the PCM to apply properly in BTMS. They also conducted a comprehensive trade-off analysis of BTMS following analysis of Cosley and Garcia (2004) [19]. Later, Pan et al. (2016) reviewed in more detail on the way to improve the low thermal conductivity of PCM [20]. Wang et al. (2016) reviewed BTMS from two aspects: thermal characteristic of Li-ion batteries and its external thermal management solutions [17]. They first examined the electrochemical/equivalent circuit models of the Li-ion batteries to understand its heat generation and investigated thermal runaway and thermal effects under the subzero temperature. Then, similar to Rao and Wang (2011), they reviewed BTMS by classifying them as air, liquid, PCM, heat pipe and combinations of them according to heat transfer mediums. Recently, Liu et al. (2017) reviewed the BTMS using the phase change process by distinguishing between the liquid-vapor phase change based method and the solid-liquid phase change based method as well as air-based and liquid-based BTMS [21]. In addition to cooling the battery, they also briefly discussed various heating methods. Xia et al. (2017) reviewed the existing BTMS in terms of cell level and module level [22]. In the cell level, the battery thermal behaviors including the amount of heat generation, heat transfer methods and thermal boundary conditions were investigated, while in the module level, various BTMS were examined. In particular, they compared the efficiency of the air-based BTMS and liquid-based BTMS respectively according to the configuration of the cells (serial, parallel and mixed) and subcategorized the indirect liquid cooling system into tube cooling and plate cooling using mini/micro-channels. The previous BTMS review papers mostly focused on heat exchange method or materials. Unlike the diverse research conducted on the battery thermal issues, there was limited discussion on the future direction of BTMS. Therefore, various BTMS in terms of thermal cycle options have been extensively reviewed and the next generation BTMS has been further discussed in this paper. Also, maximum temperature (T_{max}) and maximum temperature difference (ΔT_{max}) of the batteries derived from each BTMS study are summarized. Lastly, a novel thermal management system for thermal management of high energy density Li-ion battery is proposed.

2. Battery thermal management system

2.1. Thermal model and issues

The battery is the most important part of EVs, repeating a number of charge and discharge cycles in an external environment during its lifespan [23]. Li-ion batteries' performance is closely related to temperature, so it is important to understand how heat is generated inside the battery [24]. Heat generation inside the Li-ion batteries is a complex process that requires an understanding of how the rate of electrochemical reaction changes with time and temperature and how current flows in the battery. According to Thomas and Newman (2003), Li-ion cells are known to generate heat by the reversible entropy, resistive dissipation, relaxation of the concentration gradient of the cell and chemical reaction [25]. Simply, heat generation of the battery is presented by Gu et al. (2000) [26] in Eqn. (1)

$$\dot{Q} = I(U - V) - I\left(T\frac{dU}{dT}\right) \tag{1}$$

$\dot{Q}$, I, U and V respectively represent the heat generation rate, the electric current passing the cell, the open-circuit voltage and the cell voltage of the Li-ion batteries. The first term on the right side of the equation is about the resistance loss in the cell and the second term is related to the reversible entropic heat in the electrochemical reaction. In addition, battery thermal model has been studied according to the physical mechanism (electro-thermal model [27], electrochemical thermal model [28], thermal runaway propagation model [29]) and the dimensions (lumped model [30], 1D [31], 2D [32] and 3D [33]). In the above mentioned studies, Li-ion batteries generally generate three types of heat during charging and discharging: activation irreversible heat due to the electrochemical reaction polarization, joule heating causing ohmic losses and reversible reaction heat due to entropy change during charge and discharge. Therefore, if the battery heat generated during charging/discharging is not properly released, the temperature of the battery may increase due to heat accumulation, which may adversely affect battery performance, life and safety. A degradation in the performance of the Li-ion batteries can be characterized by a loss of capacity and power [12]. The battery capacity decreases because the active material inside the battery is converted to an inactive phase and battery power is reduced because of the increase in impedance [34]. The specific and detailed capacity/power fade mechanism is difficult to explain and complex, but it is clear that the operating temperature affects the performance of Li-ion batteries. Table 1 summarizes the effect of battery capacity on cycle repeatability under various operating temperature and discharge rate conditions. As shown in Table 1, battery capacity decreases as the cycle repeats when the temperature is above or below the proper operating temperature [35-41]. In addition, Belt et al. (2005) studied the power fade as well as the capacity fade according to the temperature and the depth of discharge (DOD) changes [42]. The research states that unlike capacity fade, power fade is a powerful function of DOD and these losses are temperature independent of small DOD changes. Another major problem caused by the heat of the Li-ion batteries is a thermal runaway [43]. Thermal runaway is a phenomenon that can lead to destructive consequences such as rapid temperature rise, gas generation and even battery explosion as the process of temperature increase is accelerated [44]. This phenomenon has a very negative effect on the safety of vehicles and passengers. To reduce the potential risk of thermal runaway, a variety of safety mechanisms have been utilized in Li-ion batteries such as safety vents, thermal fuses, automatic reset devices, shutdown separators, chemical shuttles, coatings and heat-retardant electrolytes and electrodes [45]. In addition to these safeguards, it is important to prevent non-uniform temperature of battery cells, which is the main cause of thermal runaway [46]. The temperature distribution of the battery cell may be uneven due to its thermal resistance and the internal heat generation inside the battery cell, which may be quite relevant for performance, safety and aging-related issues [47-49]. Therefore, in designing and optimizing BTMS, it is necessary to consider not only preventing an excessive temperature rise but also mitigating temperature unevenness. The specific thermal runaway mechanism of the Li-ion batteries has been reviewed by Feng et al. (2018) [50]. In addition to the problem of temperature non-uniformity and rapid rise, energy and power capabilities of Li-ion battery significantly decrease when operating at low temperatures [51-53]. The causes of performance reduction of Li-ion batteries at low temperatures are generally known as solid electrolyte interface film, surface charge transfer impedance and lithium solid diffusion in electrodes [54-57]. As a method to prevent adverse effects at low temperature, there are air conditioning (AC) heating method [58], preheating method [59] and heating plate method [60]. Zhiguo et al. (2015) investigated the performance of a 35Ah high-power Li-ion battery in a low-temperature environment and proposed a wide line metal film heating method for battery heating to significantly improve the low temperature performance [61]. As a result of examining the charge/discharge performance of the cell while varying the temperature from 20 °C to -40 °C at several different constant currents, the discharge capacity of the cell decreased as the temperature decreased and the charge was not performed well under 0 °C. However, these performance reductions could be improved by the proposed heating method. To prevent the above-mentioned Li-ion battery thermal issues, the BTMS that maintains the proper temperature range and temperature uniformity of the battery is necessary for EVs. The tendency to stack a lot of battery cells that have higher energy density than before into the pack for the increase in mileage and to charge the battery with a higher current to reduce the charging time has made the role of BTMS more important because it causes the battery to generate more heat.

2.2. Classification of battery cooling systems

The most important function of the BTMS is to maintain an optimal operating temperature range and a uniform temperature distribution within the battery cell, module and pack at high charge/discharge rates and extreme external environmental conditions [62]. According to Pesaran (2001), the BTMS should have the following four essential functions: cooling to remove heat from the battery, heating to improve the battery temperature when the temperature is too low, insulation to

Table 1
Summary of studies investigating battery capacity fade at various operating temperature conditions.

Author (Year)	Battery cathode/anode	Voltage range (V) < DOD range > (%)	Cycle rate	Number of cycle	Temperature (°C)	Capacity fade (%)
Ehrlich (2002) [35]	C/$LiCoO_2$	4.2–2.5	C/1	500	21	9
	0				45	13
	C/$LiMnO_4$				21	28
					45	51
Ramadass et al. (2002) [36]	C/LiCoO2	2–4.2	Charging C/1.8	150	25	6.09
			Discharging C/9-1C		55	9.4
				500	25	22.5
					55	70.56
				800	25	30.63
					45	36.21
Shim et al. (2002) [37]	C/$LiNi_{0.8}Co_{0.14}Al_{0.05}O_2$	< 4.1	C/2	140	25	4
		< 100% >			60	65
Amine et al. (2005) [38]	MCMB/$LiFePO_4$	2.7–3.8	C/3	100	37	55
					55	72
Liu et al. (2010) [39]	C/$LiFePO_4$	< 90 >	–	2628	15	7.5
		< 50 >		757	60	20.1
				1376	45	22.1
Jaguemont et al. (2016) [40]	$LiFeMnPO_4$	< 60 >	1C	170	25	7
		< 60–40 >		12	−20	20.8
Zheng et al. (2017) [41]	$LiFePO_4$/MCMB	< 70 >	1/3C	100	−10	12.77
		< 1 0 0 >	1/10	100		2.97
			1/2	40		30.69
			1C	20		29.33

prevent sudden temperature change of battery and ventilation to exhaust the potentially hazardous gases from the battery [14]. In addition, BTMS should have characteristics such as compactness, lightness, low cost, high reliability, easy maintenance, low parasitic power use and easy packing in order to apply to EVs [63,64]. However, this paper focuses on the cooling system of the battery because the temperature rise due to the battery heat generation is the most important, except for the initial operation in the low temperature ambient environment when driving an EV. Battery cooling systems have been classified in a variety of ways. First, battery cooling systems can be divided based on medium such as air cooling, liquid cooling and PCM cooling [18]. Another criteria is the power consumption, where passive cooling only utilizes the ambient environment while active cooling has an energy source that provides cooling [65]. Lastly, direct cooling and indirect cooling are categorized depending on whether the medium is in direct contact with the battery or not [66]. In this paper, the BTMS is classified with its thermal cycle options as shown in Fig. 1. It can be divided into two main groups: BTMS with the vapor compression cycle (VCC) and BTMS without the VCC. Three systems that use the VCC are cabin air cooling, secondary loop liquid cooling and direct refrigerant two-phase cooling. The cooling systems without the VCC include PCM cooling, heat pipe cooling and thermoelectric element cooling. The VCC of an automotive AC system, which adjusts the air condition through cooling and heating to provide a comfortable environment for passengers while operating the vehicle in various atmospheric conditions, is configured in all categories of vehicles. Therefore, integration of BTMS and VCC is applied to many EVs because it can be utilized in existing systems [67]. However, such an integrated system is disadvantageous in that it consumes a large amount of power, and therefore, a thermal management method of a battery without using VCC are studied. The schematics of each subcategorized BTMS are shown in Fig. 2. In the overall schematic diagram, the blue and green line represent the refrigerant flow and the coolant flow respectively. Fig. 2(a) shows the cabin air cooling system where the cooled air is blown from the AC system into the battery. Fig. 2(b) shows the secondary liquid loop cooling system using liquid coolant cooled by refrigerant in the chiller or outdoor air in the radiator. In this system, the refrigerant loop and liquid coolant loop are connected by the additional heat exchanger by extending the refrigerant circuit of VCC. Fig. 2(c) shows the radiator liquid cooling system, in which the high-temperature coolant that absorbed the battery heat is cooled only by air. However, this system does not apply to actual EVs because it may not cool the liquid properly due to the ambient environment conditions. This cycle was generally assumed because much research have been carried out to maintain the temperature of the liquid flowing into the battery at a constant level without detail descriptions of the system which is depicted in Fig. 2(b). Fig. 2(d) shows a direct refrigerant two-phase cooling system in which an additional heat exchanger is built into the refrigerant circuit that extends to the base VCC where the refrigerant is directly flowed into it to manage battery heat. Subsequently, the cooling systems without VCC are described in the lower part of Fig. 2. The PCM cooling system using PCM that absorbs and dissipates large amounts of heat with latent heat while maintaining a constant temperature is shown in Fig. 2(e). The heat pipe cooling system using a heat pipe which is a heat transfer device that combines the principle of thermal conductivity and phase transition is shown in Fig. 2(f). Finally, Fig. 2(g) shows a thermoelectric-element cooling system using a Peltier element that generates exothermic and endothermic reaction at the same time when a thermoelectric potential difference is given. The more specific description of the systems is explained in the following chapters.

3. Battery thermal management system with VCC

3.1. Cabin air cooling system

The BTMS using air as a medium has been applied to many EVs because it can provide a relatively simple design that can reduce production and maintenance costs [68,69]. This system can be classified into three types according to the source of the air [70]. Obviously, using only the outside air is possible while using the preconditioned cabin air through base VCC and outside air appropriately in accordance with the situation is another type. Lastly, using the cooled air from an evaporator that is additionally configured to the basic VCC in certain scenarios where the cooling requirements of the cabin and battery may be different can be considered. Namely, the appropriate type should be selected in consideration of the battery heat generation, the external environment and the driving tendency. However, many researches related to air-using BTMS only set the air temperature at the appropriate room temperature without explaining the source of the air. Thus, this paper considers the cabin air cooling system using pre-conditioned air as a medium for battery cooling. The cabin air cooling system can be realized in a way that uses pre-conditioned cabin air through the VCC of

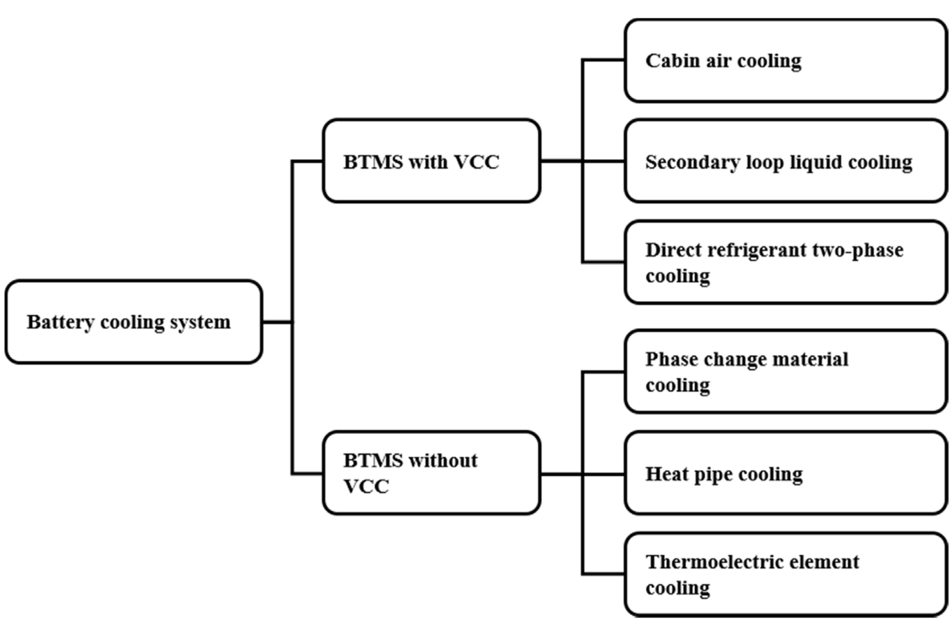

Fig. 1. Classification of battery cooling systems.

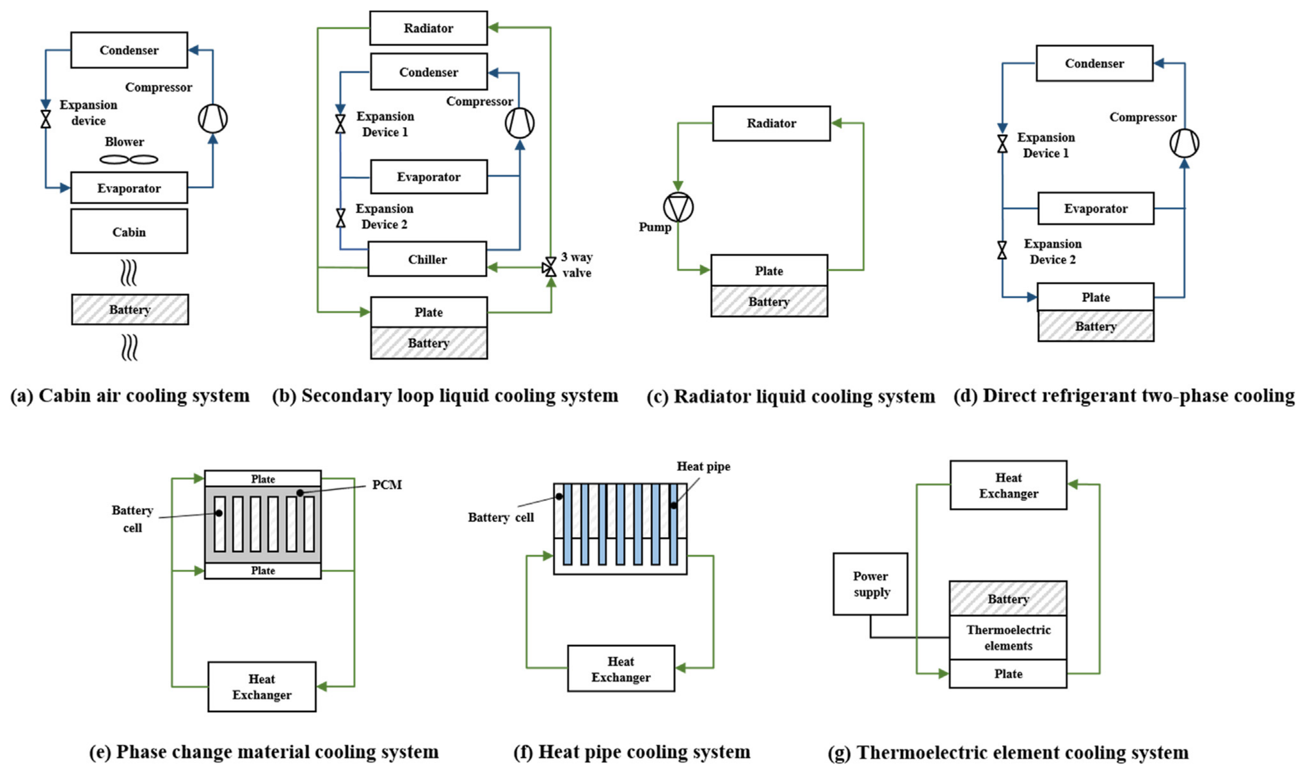

Fig. 2. Schematics of the various battery cooling system.

the EV AC system. As a result, this system only uses some of the additional components, such as fan ducts and manifolds for blowing direct cabin air into the battery. However, since air has low heat capacity and low thermal conductivity, this system may be less effective at maintaining the temperature uniform inside and between the cells of battery modules, and it is difficult to discharge considerable battery heat compared to the same flow rate of liquid [71]. In other words, this system requires a large amount of air to remove the battery heat, which results in bulky ducts and manifolds where the energy consumption of the fans is high. Furthermore, it is difficult to accumulate a lot of cells in the pack because the gap between the battery cells must be wide [65]. Other drawbacks of this system are that it has noise problems generated by multiple fans or blowers which negatively affects cabin comfort since the cabin air is used directly for BTM [68]. These disadvantages may limit the application of the cabin cooling system to an appropriate EV's BTMS with increased performance and mileage. Over the past few years, improvements of the cabin air cooling system for the Li-ion batteries have mainly focused on three aspects: the geometry of air channels, cell arrangement and air flow paths. Several studies concerning the cabin air cooling system are summarized in Table 2 based on the above criteria.

There have been many studies that improved the cooling performance by optimizing the geometry of the air flow channel since the airflow distribution of the coolant passages has a direct effect on the battery temperature. Park (2013) analyzed the cooling performance of five types of manifolds to find the optimal airflow configuration without changing the layout or design of the existing battery system [72]. The research showed that type 5 with a rectangular ventilation hole for pressure relief and emissions of harmful gases in tapered manifold extending from 10 mm to 20 mm in a vertical direction is capable of effectively controlling the temperature of the battery system while improving energy consumption over other types. Xu and He (2013) studied the heat dissipation performance of batteries in various airflow duct modes [73]. They analyzed the heat flow field of the battery pack with a longitudinal and horizontal layout and the battery pack described in Fig. 3(a) and (b). Research showed that horizontal battery packs can improve heat dissipation performance compared to longitudinal battery packs because it can shorten the airflow path and adding bottom duct increased the contact area for thermal conduction, resulting in better heat dissipation performance. In particular, the heat dissipation performance of the U-type bottom duct was superior to the 1-type bottom duct. Sun and Dixon (2014) examined the cooling efficiency of the U-type duct and the tapered Z-type ducts described in Fig. 3(c) and (d) [74]. Simulation results showed that using the tapered Z-type ducts can significantly reduce the air flow rate changes in the cooling channels and mitigate cell temperature changes and overall pack pressure drop compared to the U-type ducts. The uniformity of the battery cell temperature depends on the uniformity of the air velocities in all the cooling channels, but the inconsistency of the pressure drop between the cooling channels results in an inconsistency in the air velocities in the cooling channel. In order to improve the uniformity of the pressure drop across the cooling channels, Chen et al. (2017) also investigated the effect of the cooling performance of the BTMS by arranging the widths of the inlet divergence plenum and the outlet convergence plenum without changing the layout of the battery cells [75]. They used the flow resistance network model to calculate the airflow distribution, newton method to minimize the standard deviation of the airflow velocity of the channel and computational fluid dynamics (CFD) method to calculate airflows of BTMS. The study suggested that the ΔT_{max} of the optimized battery pack can be reduced by 41% in the fixed inflow flow rate and constant heat generation situation. Xie et al. (2017) examined the effects of air inlet/outlet angles and widths to optimize the air-cooling structure to reduce the ΔT_{max} and the T_{max} of battery packs [76]. They optimized the air cooling structure by orthogonal measurement method based on the three design factors mentioned above. The study showed that the best thermal performance was achieved with 2.5° air inlet angle, 2.5° air outlet angle and evenly distributed battery cell conditions while the T_{max} and temperature difference were reduced by 12.82% and 29.72%, respectively, after multipurpose optimization. Hong et al. (2018) investigated the effect of changing the position and size of the additional secondary vent located in the wall of the outlet duct on the cooling performance of BTMS [77].

Table 2
Summary of studies on air cooling in Li-ion batteries.

Major design variable	Author (Year)	Li-ion Battery	Battery cell capacity (Ah)	$T_{inlet\ air}$ (°C)	SOC (%)	Battery load	T_{max} (°C)	ΔT_{max} (°C)
Geometric of air flow channel	Park. (2013) [72]	72 prismatic cells	5.19	40	–	4.81 W	58.2	18.2
	Xu and He (2013) [73]	48 prismatic cells	55(pack)	20	70–100	5.69 W	6.50(T_{max} rising)	1.96
	Sun and Dixon (2014) [74]	80 pouch cells	–	25	50	US06 drive cycles	< 34 (z-type flow pack with tapered duct and secondary duct)	1.1
	Chen et al. (2017) [75]	24 pouch cells	2.2	27		6.5 W	56.05	7.4
							42.55	3.5
							40.25	2.8
							37.85	2.4
	Xie et al. (2017) [76]	10 prismatic cells	–	25		3.82 W (each cell)	34.45	4.47
	Hong et al. (2018) [77]	24 pouch cells	2.2	27	95–5	5C	51.85	3.7
Cell layout	Fan et al. (2013) [78]	8 prismatic cells	15	27	–	6.2 W	33.53 (gap spacing 3 mm)	2.81 (cell)
	Wang et al. (2014) [79]	25 cylindrical cells	1.5	25	–	3C	33.9 (5 * 5 cell layout),	2.95
	Yang et al. (2015) [81]	60 cylindrical cells	3.3	25	–	2C	34.55 (Aligned cell layout)	0.93,
Air flow path	Mahamud and Park (2011) [82]	8 cylindrical cells	3.6	20	70–100	7C	29.6 (average temperature in the reciprocating air flow)	4
	Yu et al. (2014) [83]	12 prismatic cells	180	24	100	1C	33.1	< 5
	Lu et al. (2016) [84]	252 cylindrical cells	–	20	–	$0.58\cdot10^{-3}$ W	36.85 (59 air vents)	16

Their numerical study showed that when the secondary duct was located on the convergence plenum around the battery cell with the highest cell temperature, the T_{max} of the battery pack was reduced by more than 5 K and the temperature difference reduced by more than 60% compared to the original system without an additional vent.

Another major design variable that affects the cooling performance is the cell layout. Fan et al. (2013) performed three-dimensional transient thermal analysis of the battery module while changing the cell gap spacing and flow rate of fan [78]. They found that decreasing the cell gap spacing or increasing the fan flow reduced the T_{max} rise of the module but the gap spacing should be of moderate size to achieve better temperature uniformity. Wang et al. (2014) studied the thermal performance of battery modules in various cell layouts (1x24, 3x8, 5x5 rectangle arrays, 19 cells hexagonal arrays, and 28 cells circular arrays) and in various fan position to improve temperature uniformity within the module [79]. This study described that the optimum cooling performance is obtained when the fan is located at the top of the module, the rectangular cell layout arrangement is 5×5 considering cooling capability and the hexagonal structure consisted of 19 cells considering space utilization. They also developed a transient thermal model of a three-dimensional 5×5 rectangular cell array module based on an empirical heat source model to characterize the thermal behavior of the Li-ion battery in the following year [80]. Yang et al. (2015) discussed the thermal performances of the battery pack in which the arrangement of 6×10 cylindrical battery cells are in a staggered or aligned arrangement [81]. As a result of studies under constant air flow rates, the T_{max} rise is proportional to the longitudinal spacing of staggered arrays, but inversely proportional for aligned arrangements and increasing the transverse spacing increased battery temperature rise in both the aligned and staggered arrays arrangement. Also, considering the temperature rise, temperature uniformity, power consumption and cooling index, battery pack with longitudinal interval and transverse interval of 34 mm and 32 mm, respectively, were most reasonable.

Studies that improved the cooling performance of the battery by changing the air flow path have also been thoroughly conducted. Mahamud and Park (2011) studied a reciprocating cooling system that periodically reverses the flow of air to mitigate the inherent temperature uniformity problem of existing unidirectional air flows systems [82]. The numerical results show that the reciprocating flow of 120 s period can reduce temperature difference of battery cell by 72% and maximum cell temperature by 1.5 °C compared to unidirectional flow method due to the thermal redistribution and disturbance of the boundary layers formed in the cell. Yu et al. (2014) proposed a new BTMS that includes a common air channel in which air flows in one direction, an air channel at the bottom of the pack with vertical turning air channels and jet holes for mitigating the heat accumulations in the battery pack [83]. Research shows that the proposed system has significantly improved heat accumulation in the intermediate cells and ΔT_{max} in each cell did not exceed 5 °C. Lu et al. (2016) numerically investigated air cooling performance in two kinds of flow paths (15 and 59 vents) and air flow rates through a densely packed battery box with 252 cylindrical Li-ion batteries and five air baffles [84]. They found that the densely packed battery box with 59 vents further reduced T_{max} and ΔT_{max} compared to the 15 vents case due to the improvement in effective heat transfer area between the air coolant and the battery surface.

In addition, various studies have been conducted to develop thermal models for the cabin air cooling system other than the above mentioned improved designs. Choi and Kang (2014) proposed a simple modeling methodology that describes the thermal behavior of an air-cooled Li-ion battery system [85]. The proposed model was developed from the appropriate heat transfer assumptions and the model was verified with the vehicle driving test results. Xun et al. (2013) developed a numerical and analytical model to investigate the thermal behavior of flat and cylindrical Li-ion batteries during discharge [86]. Because they could not find relevant experimental data, they were regarded as evidence for the

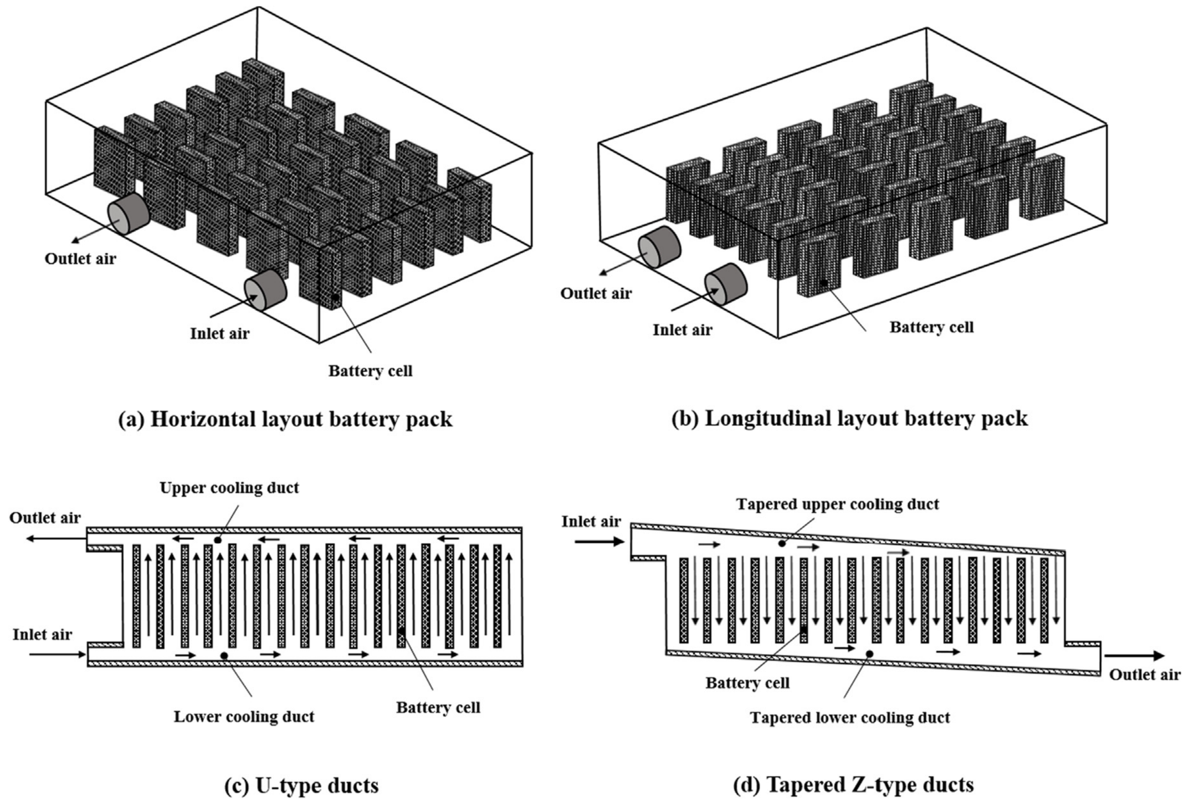

Fig. 3. Schematic of the ducts type and battery pack layout [73,74].

rationality of the model by comparing numerical and analytical models. Zhu et al. (2013) developed an electrochemical-thermal model of the Li-ion battery pack with forced air cooling system based on a porous electrode and concentrated solution theory [87]. The developed model was verified by charge/discharge cycling experiments under natural and forced convection conditions.

3.2. Secondary loop liquid cooling system

The cabin air cooling system may not be suitable for most high-performance EVs because there is a limit of extracting the heat with air. In order to overcome the drawbacks of air-based cooling, the secondary loop liquid cooling system can be applied. A schematic diagram of the secondary loop liquid cooling system is depicted in Fig. 2(b). This figure shows BTMS consisting of two loops. The refrigerant loop marked with the blue lines and the liquid coolant loop indicated by the green lines are connected by the chiller. The flow of liquid coolant is controlled through a three-way expansion valve depending on the cooling load and the external environment. When the battery requires low cooling performance and when the ambient temperature is lower than the liquid coolant temperature, the liquid coolant flows to the radiator cooled by the outside air. When the battery needs high cooling performance or when the ambient temperature is higher than the liquid coolant temperature, the coolant flows to the chiller to exchange heat with the refrigerant. Considering the heat pump system by extending Fig. 2(b), the battery can be heated as well as cooled by changing the flow direction of refrigerant through the multi-way valve. Most studies on the BTMS using medium liquids assume that the liquid temperature is maintained within a certain temperature range without specific explanations of the cooling system which is represented in Fig. 2(c).

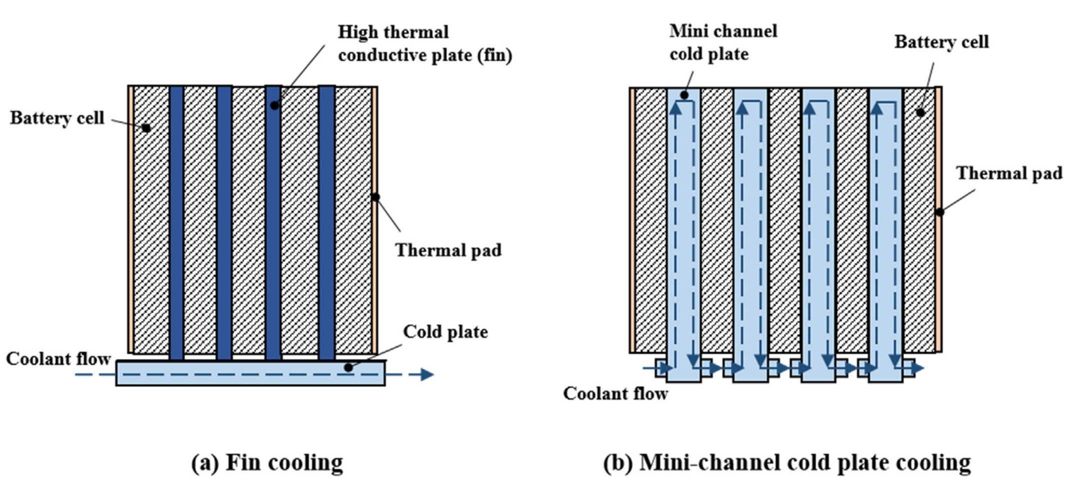

Fig. 4. Schematic diagram of the secondary loop liquid cooling system in battery module unit.

However, because the battery temperature needs to be properly managed at various battery loads and ambient temperatures, the actual EVs use the secondary loop liquid cooling system for BTMS [88,89]. The main advantage of the secondary loop liquid cooling system is that it can maintain the proper temperature of the battery in a very compact pack design under extreme climatic conditions such as rapid charging and discharging at high atmospheric temperatures. This is because it uses a liquid coolant with higher mass flow, higher heat capacity and faster heat transfer rate than air. However, due to the additional components and refrigerant/coolant piping, this system can be a more complex system compared to the cabin air cooling system, which can result in increased weight, errors, maintenance effort, and a risk of leakage [88].

There are two types of secondary loop liquid cooling systems in the module/cell unit depending on the arrangement and type of heat sink plate. The schematic diagrams of the two methods are shown in Fig. 4. Fig. 4(a) describes a fin cooling method in which a series of affixed fins between battery cells are thermally attached to a single cold plate. In this method, the heat of the cells is distributed to the fins, which is then transferred to the liquid coolant flowing in a single cold plate and discharged to the outside. This method can reduce the temperature difference in the cell level by redistributing the locally high heat flux of the cell through the fin with high thermal conductivity. The disadvantage of this method is that since the liquid flowing in the single cooling plate is cooled from the front fins, the cooling performance deteriorates gradually as the temperature difference between the liquid and the fin gradually decreases. Fig. 4(b) shows a method of attaching a highly thermally conductive mini-channel cold plate directly between cells, which is called a mini-channel cold plate cooling method. This method can reduce the disadvantages of fin cooling by keeping the temperature distribution uniform among the cells by simultaneously flowing liquid to the mini-channel cold plates attached between the cells. However, this method generally requires a long and narrow channel, resulting in a high pressure drop. Therefore, electric coolant pump with higher flow rates and higher static pressures should be required. In other words, this means that high power consumption is required.

Similar to cabin air cooling, studies related to secondary loop liquid cooling system have focused on pack, module and cell unit BTM rather than whole system BTM. In particular, there was a variant of studies using a channel rather than using a fin. The cooling performance of the mini-channel cold plate and pressure drop of liquid coolant are determined by the geometry of the channel. Therefore, optimizing the shape of the channel and optimizing the liquid flow direction or number of channels and examining the effect of cold plate under various operating conditions were mainly focused in much research over the last few years. The studies that optimize the mini-channel cold plate in the secondary loop liquid cooling system are summarized in Table 3.

In the case of optimizing the geometry of the channel, Jarrett and Kim (2011) studied the optimization of a single serpentine channel cooling plate by varying the width and position of the channel for each of three objective functions: pressure drop, mean temperature and temperature uniformity [90]. As a result of the optimization, the optimum design for the lowest mean temperature and the lowest pressure drop were almost the same in a way that maximizes the possible channel width, but the design for temperature uniformity was a narrow inlet channel structure widening toward the outlet. Therefore, their research limited the ability to provide information on intermediate designs considering all three optimal variables because they required the trade-off for one purpose in order to realize improvement in other design. In their later study [91], they analyzed the performance of the cooling plate by changing three types of boundary conditions (coolant flow rate, the magnitude and distribution of heat generation), unlike the previous study. The results show that the optimization of temperature uniformity is sensitive to both distributions of the input heat flux and the coolant flow rate, while the optimization of the average

Table 3
Summary of studies of liquid cooling methods using mini-channel cold plates.

Major design variable	Author (year)	Li-ion Battery	Liquid (plate type)	Battery load	Number of channel in single plate	$T_{inlet\ liquid}$ (°C)	T_{max} (°C) (condition)	ΔT_{max} (°C)
Geometry of the channel	Jarrett and Kim (2011) [90]	Heat flux (instead of single rectangular cell)	Water/ethylene glycol (single serpentine channel plate)	2.56 W	1	26.9	32.14 (T_{avg} at P optimized) 32.1 (T_{avg} at T_{avg} optimized) 35.16 (T_{avg} at $\mathbf{T}_{\sigma}$ optimized)	2.53 2.32 1.22
	Jarrett and Kim (2014) [91]	Heat flux (instead of single rectangular cell)	Water/ethylene glycol (single serpentine channel plate)	16 W 16 W 6.4 W 32 W	1	26.9	40.67 29.58 29 37.4 (Conditions optimized for T_{avg})	6.31 1.33 1.04 4.95
	Jin et al. (2014) [92]	3 cartridge heater	Water (oblique channel plate)	220 W 1240 W	1	–	< 50 < 50	–
Number of channel and flow direction of coolant	Huo et al. (2015) [93]	Rectangular cell (7Ah)	Water (straight channel plate)	5C	2–6	25	58.40 (6 channel conditions and after 720 s)	9.02
	Zhao et al. (2015) [94]	40 cylindrical cells (10Ah)	Water (cylinder)	5C	2–16	25	< 39 (8 channels conditions and after 840 s)	< 12
	Qian et al. (2016) [95]	3 rectangular cells	Water (straight channel plate)	5C	2–7	25	35.2 (5 channels with 2 cold plate and after 720 s)	9
	Lan et al. (2016) [96]	1 prismatic cell (55Ah)	- (straight aluminum channel plate)	1C 1.5C 2C	4–16	27	27.81 (after 3600 s) 27.9 (after 2400 s) 28.21 (after 1800 s)	0.8 0.9 1.21
	Wang et al. (2017) [97]	1 prismatic cell (20Ah)	Water(silica plate)	3C 5C	1–7	30	39.1 2 (5 channel)	–

temperature is only sensitive to the heat flux distribution and the optimization of the pressure drop is not sensitive to the tested boundary conditions. Jin et al. (2014) proposed a new oblique mini-channel liquid cold plate that has cut obliquely to the straight channel to prevent the decreasing of the convection heat transfer from the inlet to the outlet [92]. Experimental results showed that the cooling performance of the proposed plate is better than the conventional straight channel plate by keeping the surface temperature below 50 °C and maintaining the low flow rates of 0.1 $l{\cdot}min^{-1}$ and 0.9 $l{\cdot}min^{-1}$ under the heat load of 220 W and 1240 W, respectively.

The optimization studies of the number of channels and flow direction of coolant is another important aspect. Huo et al. (2015) investigated the influence of temperature rise and distribution of a single pouch type rectangular battery while changing the channel number, flow direction, inlet mass flow rate and ambient temperature during the 5C discharge process assuming that the Li-ion battery and the cold plate are homogeneous and isotropic [93]. As a result of this study, the temperature distribution tends to decrease more rapidly as the number of cooling channels increases, and when the inflow flow rate increases, the battery cools more efficiently. However, because there are an optimal mass flow rate and the number of cooling channels, the system efficiency decreases beyond that optimal point. Zhao et al. (2015) numerically investigated the effects of the heat dissipation performance of a cylindrical battery with mini-channel liquid cooled cylinder by changing the channel volume, mass flow rate, flow direction and inlet size [94]. The results show that T_{max} can be controlled below 40 °C when the number of channels is 4 or more when the inlet mass flow rate is 10^{-3} $kg{\bullet}s^{-1}$ Also, considering the appropriate difference between T_{max} and the local temperature, this system can be advantageous than natural convection cooling only when the number of the channel exceeds eight. Qian et al. (2016) also used simulations to compare the thermal behavior of the half of pack with five battery cells by changing the number of cold plates, inlet mass flow, flow direction and number of channels [95]. Lan et al. (2016) developed a new design of a BTMS based on a strip with mini-channel tubes instead of a plate in a single prismatic battery cell [96]. They investigated the T_{max} and ΔT_{max} across the cell and the temperature uniformity inside the cell by varying the number of strips and mini-channels, discharge rate and flow directions and flow rates of liquid. Their research has shown that cooling performance of BTMS can be achieved when all the flow inlets are aligned along one side of the battery and more mini-channels are used under the same total flow rate. Mostly, the above-mentioned studies were about directly contacting mini-channel cold plate to battery cell without considering the collision between rigid bodies. However, this can damage the cold plate and cause liquid leakage and other problems. Thus, Wang et al. (2017) proposed a silica-liquid cooling plate (SLCP) consisting of thermal silica plates and copper tubes for BTMS [97]. They then investigated the cooling capability of the proposed BTMS through experiments and simulations at a different number of silica plates and channels, flow rates and flow directions under three discharging rates. As a result of this study, the cooling performance was increased as the number of thermal silica plates and liquid channels increased, but the flow direction was not important. In addition, the proposed system with five channels had a T_{max} of 39.1 °C below 3C discharge rate and inlet flow rate of 0.1 $m{\bullet}s^{-1}$.

The thermal behavior of a battery or working fluid is investigated as the operating conditions vary without changing the shape of the channel. Panchal et al. (2017) studied the temperature and velocity distributions of liquid coolant in mini-channel cooling plates experimentally and numerically at different discharge rates and coolant temperature conditions [98]. Malik et al. (2018) also performed a thermal analysis of battery packs combining three battery cells and four cooling plates at various discharge rates, drive cycles and liquid temperatures [99]. As a result of the parametric study, liquid at 30 °C was best suited for cooling battery packs because the maximum and average temperature of the battery pack remained within the battery's proper temperature range of 25–40 °C at a discharge rate of 1C to 4C. Rao et al. (2017) designed a new liquid cooling-based BTMS that directly connected the aluminum block to the cylindrical Li-ion battery and allowed cooling water to flow through that block to cool the battery, unlike the conventional method in which a cooling plate is attached to a prismatic battery cell [100]. They investigated the effect of aluminum block length and coolant inlet velocity on thermal performance in the proposed system. The results show that the T_{max} and ΔT_{max} decrease with increasing contact area by increasing the length of the block and inlet velocity.

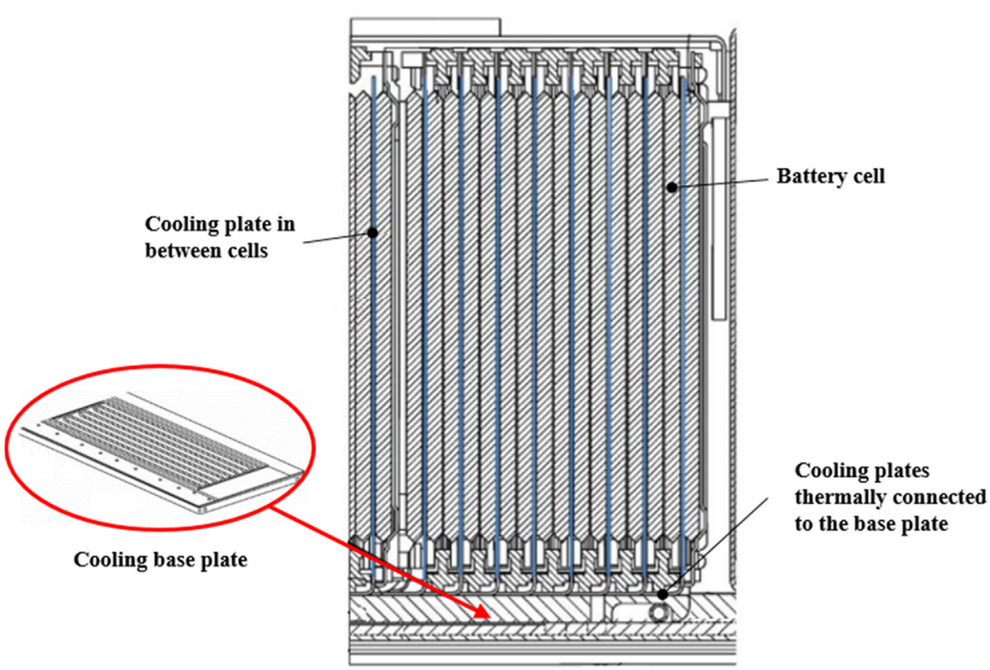

Fig. 5. Schematic diagram of direct refrigerant cooling system [103].

Table 4
Summary of studies of phase change material cooling system.

Additional PCM cooling mode	Author (year)	Li-ion Battery	Battery capacity (Ah)	PCM	Thermal conductivity of PCM ($W \cdot m^{-1}K^{-1}$)	Battery load	T_{amb} (°C)	T_{max} (°C)	ΔT_{max} (°C)
Forced air convection cooling	Ling et al. (2015) [119]	20 cylindrical cells (5S4P)	2.6(cell) 10.4(module)	RT44HC/EG composite	7.85(composite)	2C	25	< 46	< 3
	Wu et al. (2017) [122]	12 prismatic cells (6S2P)	12(cell)	Paraffin/EG /pyrolytic graphite sheets(PGS)	0.3(pure) 129(EG) 800(PGS)	5C (after discharge/ charge 5cycle)	25	35.65 (module)	< 2
Heat pipe cooling	Zhao et al. (2017) [123]	Cylindrical heating rods (4S3P)	–	Paraffin/EG composite	0.283(pure) 3.14(composite)	5C	20	56	< 7
Liquid cooling	Hémery et al. (2014) [124]	Electric heater	–	Paraffin wax (RT28HC)/ aluminum fin	0.2(pure)	11.1 W	22 (liquid temp)	< 35	–
Free convection cooling	Hallaj and Selman. (2000) [114]	8 cylindrical cells (4S2P)	100(cell)	Paraffin wax	0.29(solid) 0.21(liquid)	C/1	–	–	< 2 (between cells)
	Kizilel et al. (2008) [126]	16 cylindrical cells (8S2P)	2.2(cell) 4.4(pack)	Paraffin wax(RT-42)/ graphite composite	16.6(composite)	1C	25	< 45	4
	Sabbah et al. (2008) [65]	68 cylindrical modules (4S5P)	1.5(cell)	PCM/graphite composite	16.6(composite)	6.67C	45	< 55	–
	Kizilel et al. (2009) [116]	cylindrical cells (67modules;5S4P)	1.5(cell) 7.5(module)	Paraffin wax/graphite composite	16.6(composite)	6.67C	40	47.5 (mean ,cell)	< 0.2 (cell)
	Rao et al. (2015) [127]	24 cylindrical cells (12S2P)	10(cell) 20(module)	Paraffin/copper foam	0.2(pure)	5C	33	42.33	4.08
	Wu et al. (2016) [128]	5 rectangular Li-ion cells	12(cell)	Paraffin/EG/copper mesh	0.26(pure) 7.65(composite)	5C	31	61.6	2.7
	Lv et al. (2016) [121]	24 cylindrical cells (6S4P)	2(cell) 8(pack)	Paraffin/EG/polyethylene (L-CPCM)	0.16(pure) 1.38(L-CPCM)	1C 2.5C 3.5C	30	38.5 47.6 52.6	3.6 3.9 5.7
	Duan and Naterer (2010) [125]	Electric heater	–	T-PCM 92	2.23(pure)		25	< 65	–
	Javani et al. (2014) [129]	1 prismatic cell	–	n-octadecane	0.358(solid) 0.152(liquid)	4.45 W	21	35.28	3.38
	Javani et al. (2014) [130]	4 pouch cells	–	n-octadecane/porous form	0.358(solid) 0.152(liquid)	3C	21	30.7	1.2(cell)
	Wu et al. (2018) [131]	1 prismatic cell	12	PCM/EG composite	7(composite)	5C	25	53	5

3.3. Direct refrigerant two-phase cooling system

The direct refrigerant two-phase cooling system is a relatively recent BTMS [101]. This system can be a method to mitigate the complex secondary liquid cooling system with multiple circuits by integrating battery cooling directly into existing VCC [102]. As shown in Fig. 2(d), it consists of an additional evaporator in the battery pack. This evaporator is designed in parallel with the AC evaporator by extending the refrigerant circuit to the existing VCC. The specific connection between the battery and the additional evaporator is shown in Fig. 5 [103]. The cells are connected to fins with high thermal conductivity, which are thermally connected to an additional heat exchanger. This is similar to fin cooling in the secondary battery cooling system except for the difference in the use of refrigerants that offers higher cooling rates than liquid glycol that is often used as a liquid coolant. The system also has an additional expansion device. This device is used to control the refrigerant flow to the additional evaporator according to the thermal load of the battery. The advantages of this system are that it can reduce weight and can even be more compact in design than the secondary liquid cooling system by eliminating the need for liquid coolant loop and chiller [104]. This option can effectively absorb a large amount of heat because this system uses latent heat of the refrigerant. In addition, the refrigerant-side temperature is maintained during evaporation, so that the same temperature can be used for the battery thermal management. This means that a very uniform temperature distribution of the battery can be achieved by obtaining a uniform temperature level of the entire cooling surface and the proper temperature of the battery can be maintained at a low flow rate. However, because the two evaporators are connected to a single refrigerant circuit, this system can cause a conflict of objectives due to very different load profiles for cabin AC and BTM. In the event of a collision, the thermal comfort of the passenger may be adversely affected because it is prioritized that the refrigerant is used for BTM for safety reasons [105]. Therefore, the proper control strategy of refrigerant flow is very important. Furthermore, this system can have a large power consumption since the compressor must be operated regardless of the cabin AC. Lastly, it is difficult to heat up the battery without additional heaters unless a heat pump system is considered [106,107].

There are very few studies on direct refrigerant two-phase cooling systems for BTMS. Krüger et al. (2012) investigated the thermal behavior of the battery cooled by a direct refrigerant cooling system using R134a and R1234yf during New European Drive Cycle (NEDC) on hot weather conditions [108]. Research showed that both refrigerants kept the T_{max} of the battery below 40 °C during NEDC, but ends in a temperature that is 2 K lower for the battery in the R1234yf cycle. The energy consumed for battery cooling during the NEDC was 60 kJ for R134a cycle, which was about 40% of that of R1234yf cycle. Kritzer et al. (2014) studied the use of CO_2 refrigerants of the air conditioning systems to meet emergency cooling requirements as a precaution just before the Li-ion battery thermal runaway becomes uncontrollable [109]. They configured an additional tube circuit to allow the refrigerant to pass from the AC system to the battery, then overcharge the normal capacity 4Ah battery cell at an initial 85% SOC state with a charge rate of 5C, and after reaching a voltage of 8.4 V, the battery cell was cooled by a 20 s pulse of expanded CO_2 (approx. 50 g). As a result, the front cell temperature immediately dropped from 93 °C to -49 °C, and the cell surface temperature increased again after the CO_2 pulse stopped. Although there exist few studies on the direct refrigerant two-phase cooling system yet, much more research is to be expected to be conducted in the near future on the battery-operated thermal management system of EVs with the advance of simpler, better in heat transfer and lower in cost systems.

4. Battery thermal management system without VCC

4.1. Phase change material cooling system

PCM is a material that accumulates or emits heat by using a process of changing from one state to another at a certain temperature. This has been widely used in many industries such as civil and energy engineering because it can absorb or release large amounts of heat through phase change processes without energy consumption [110-112]. In recent years, as the energy density and load of batteries have increased, BTMS has been using a powerful cooling system that uses many channels of liquid cooling loops. However, such a system has disadvantages that the complexity of the system increases and the power consumption of the compressor increases. One way to mitigate these disadvantages is the PCM cooling system [115], briefly shown in Fig. 2(e) . As shown in Fig. 2(e), the cells are directly attached to the PCM, which is generally a solid material block machined or molded so that the cells can be inserted. There are also two plates on the top and bottom or right and left sides of the PCM to release the heat absorbed by the PCM. When the battery is charged or discharged, heat is generated in the cells, and this heat is transferred to the PCM, which is in direct contact with the cells due to the conduction phenomenon depending on the temperature difference. PCM first absorbs heat as sensible heat, and then absorbs a large amount of latent heat until the end of the phase change process at a constant temperature when it finally reaches the melting point as the temperature gradually rises. This means that it can cope with the drastic thermal load of the battery without abnormal temperature rising and significant temperature unevenness [118]. However, when only PCM is used as BTMS, it is difficult to operate continuously if the PCM is completely melted due to hot weather or continuous charge/discharge cycles of the battery [119]. Therefore, additional cooling systems that release the heat of the PCM to the outside are essential and very important. Although increasing the PCM mass has the benefit of delaying the phase change completion time, it will not be able to reduce energy consumption, which is important for using PCM, because it increases the weight and reduces EV performance. So, the appropriate PCM mass must be determined. Another important factor to be considered in the application of PCM to BTMS is to select the appropriate PCM. The proper PCM should have characteristics of high latent heat, high heat capacity, high thermal conductivity and phase change temperature within the operating range of the battery. Moreover, the PCM should be chemically stable and nontoxic with low or no sub-cooling effect in the freezing process [113]. Comprehensively, paraffin is considered the most suitable material, but it has a fatal disadvantage of having a low thermal conductivity similar to most PCM's [120]. This means that it is slow to respond to high-demand applications. Therefore, there have been many studies to improve the thermal conductivity of PCM without significantly affecting the good characteristics. There are three methods for improving the thermal conductivity of PCM: adding thermally conductive material such as carbon-nano powder, adding metal fins, adding porous material such as an expanded graphite matrix (EGM). Studies on these methods were reviewed in detail by Pan et al. (2016) [20]. Despite efforts to improve the low thermal conductivity problem, PCM is still difficult to apply to automotive BTMS due to problems such as leakage, poor mechanical properties and low surface heat transfer between the PCM and the external environment .

Studies related to the PCM cooling system over the last few years have focused on improving the thermal conductivity of PCM to improve cooling performance. However, in this paper, the PCM cooling system was reviewed considering the secondary PCM cooling which serves to re-solidify the melted PCM that is essential for PCM application to BTMS as well as the thermal conductivity. Table 4 summarizes the PCM cooling system by classifying it according to the secondary cooling system of PCM that plays a critical role in recovering thermal energy storage capacity of PCM including natural convection cooling, forced convection cooling, liquid cooling and so on. Some studies about PCM BTMS combined with forced air convection cooling are as follows. Ling et al. (2015) compared battery thermal management performance of system using only PCM and system that integrates PCM with forced air convection cooling [119]. They used a battery pack surrounded by RT44HC/ expanded graphite (EG) composite with proper melting temperature and high specific phase change enthalpy in 20 cylindrical Li-ion cells arranging five cells in series and four cells in parallel. As a result of their research, T_{max} of the battery pack using only the PCM exceeded 60 °C in two cycles. In systems with PCM and forced convection air cooling, the T_{max} of pack successfully controlled below 50 °C in all cycles, even when the air temperature rose by 7 °C. Wu et al. (2017) proposed a pyrolytic graphite sheets (PGS) as a method to improve the heat transfer of PCM. And they compared the cooling performance of the paraffin/EG composites based battery module with and without the PGS by changing the convective heat transfer coefficient [122]. As a result, PCM and PCM/PGS modules were found to be ineffective to transfer the heat absorbed by the PCM to the atmosphere when the convective heat transfer coefficient was 10 W•m^{-2}K^{-1}. However, when the coefficient was 50 W•m^{-2}K^{-1}, the stable stage was reached after the first cycle, which showed the same temperature profile as the previous cycle. In addition, the PCM/PGS module provided much better heat dissipation performance and temperature uniformity than the PCM module during the five discharge/charge cycles. A few studies to cool PCM using heat pipes and to cool PCM using liquid are as follows. Zhao et al. (2017) experimentally tested the PCM/HP coupled BTM module in detail by using the heat pipe to release heat from the PCM [123]. They also used air as a method of cooling the condensation part of the heat pipe and examined the thermal behavior of the battery cells while changing the air velocity. Research showed that PCM/HP-based BTMs can maintain the T_{max} below 50 °C longer than air-based and PCM-based BTMS. Hémery et al. (2014) developed PCM-based BTMS with active liquid cooling system in order to solidify the melted PCM [124]. They constructed the system by attaching two cooling plates with water circulation at above and below the aluminum cans containing the PCM and by replacing the cells with electric heaters. As a result of the solidification test, the PCM was successfully solidified when the battery was rapidly charged at 2C rate after discharge three driving cycles while the water temperature was kept constant at 22 °C. This means that they can continue to respond to battery thermal loads with their proposed system. Duan and Naterer (2010) investigated the temperature of the heaters with two different PCM designs by immersing them in a bath containing liquid controlled at a constant temperature [125]. The first design installed a heater in the center of a cylindrical container filled with PCM and the second design wrapped a heater with a jacket of other PCM. As a result of the study, both configurations showed excellent effects in maintaining the heater within the desired temperature range. The studies to cool PCM to natural convection of air are as follows. Hallaj and Selman (2000) investigated and first proposed a PCM-based BTMS for EVs applications [114]. They simulated the temperature distribution of the EVs battery module, which consists of eight 100Ah cylindrical batteries cooled by PCM using commercial finite element software. Simulation results show that the temperature profile of the cells integrated in the module was more uniform than without PCM. Also, the temperature rise of cells with PCM was 53 K at the end of the C/1 discharge rate with h = 6.4 W•m^{-2}K^{-1}, but after 24 h of relaxation, the temperature of cells was 10 K higher than the initial temperature. Kizilel et al. (2008) has tested various cell placement and discharge rates to study the effect of PCM/graphite matrix on the stability and performance of battery packs [126]. As a result, the battery pack with PCM composite had lower cell surface temperature, slower temperature rise and lower capacity fade than without PCM. They also compared the two cooling modes by mathematical thermal modeling [116]. Sabbah et al. (2008) compared the effects of using PCMs and forced air cooling on various discharge rates, operating temperatures and ambient temperatures to cool small Li-ion batteries suitable for PHEV propulsion [65]. The results showed that the battery pack using PCM maintained the battery cell temperature below 55 °C at a constant high discharge rate of 6.67C and high ambient temperature of 45 °C without additional power consumption. On the other hand, forced air cooling consumed considerable fan power to achieve the same conditions. Rao et al. (2015) designed a battery thermal management system using paraffin/copper foam to improve the heat transfer of phase change materials and experimentally investigated thermal performance [127]. Wu et al. (2016) developed copper mesh-precipitated paraffin/expanded graphite composites to create proper BTMS by improving the low thermal conductivity of existing phase change materials, weaker framework strength and leakage [128]. Lv et al. (2016) proposed the first use of low fins in the proposed model coupled with inhibition of expanded graphite (EG), paraffin and low density polyethylene (LDPE) to dissipate the heat normally absorbed by the PCM to the outside air environment effectively [121]. The proposed TMS model is shown in Fig. 6. They investigated the temperature distribution of the battery cell during discharging at different speeds and different cooling conditions in a structure where the PCM contacted the cylindrical Li-ion battery cells. Javani et al. (2014) compared the temperature variation and distribution with the case where PCM was not applied while changing the thickness of the PCM contacting the Li-ion battery cell [129]. Their results show that the use of PCM for the BTMS results in uniform distribution of the battery cell temperature when not in use, and as the PCM thickness is increased from 3 mm to 12 mm, the battery T_{max} is further reduced from 2.77 K to 3.04 K. They also studied the thermal behavior of battery packs arranged between a thin foam sheet in which n-octadecane wax was absorbed. The T_{max} of the system when absorbing PCM on dry foam was reduced to 7.3 K [130]. Wu et al. (2018) studied the effect of PCM plate configuration, PCM thickness and convective heat transfer coefficient on thermal performance of PCM-based BTMS to optimize thermal

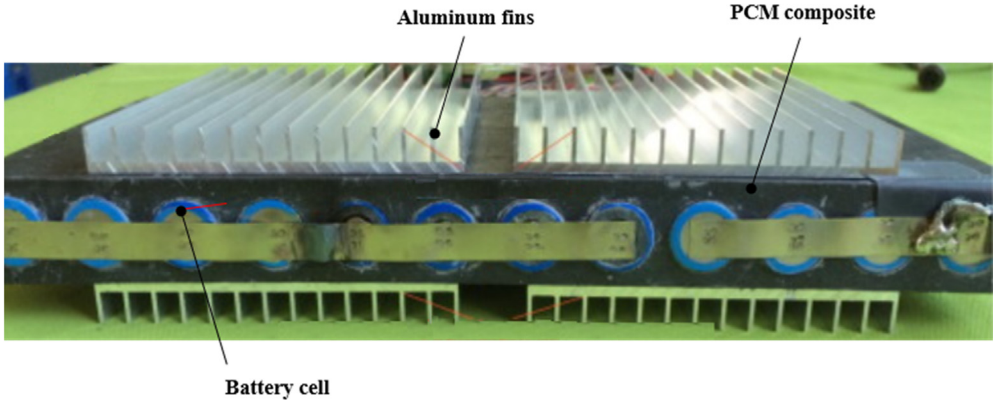

Fig. 6. Schematic diagram of the BTMS consisting of LDPE/EG/paraffin composite PCM with battery cells and aluminum fins [121].

Table 5
Summary of studies of heat pipe cooling system.

Condenser end cooling method	Author (Year)	Li-ion Battery	Battery capacity (Ah)	Heat pipe	Heat pipe working fluid	Battery load	T_{amb} (°C)	T_{max} (°C)	ΔT_{max} (°C)
Air cooling	Wu et al. (2002) [133]	1 cylindrical cell	12	2	–	C/1.2	15	32	–
	Tran et al. (2014) [134]	Electric heater (instead of cylindrical cells)	6.5	28 copper tube heat pipe	water	38 W 54 W 84 W	–	29.62 33.64 41.91(cell)	–
	Ye et al. (2015) [135]	2 electric heaters (instead of prismatic cells)	–	4 tubular heat pipe with flat shape in evaporation section with 2 copper plate	water	100 W	–	43.3	2.9
	Zhao et al. (2015) [136]	4 prismatic cells (4S1P)	3 8	aluminum flat heat pipe	acetone	3C	24.85	31.8	0.7(cell) 2.2(pack)
	Liu et al. (2016) [137]	5 prismatic cells	50	12 copper flat heat pipe with fins	water	1C 2C 3C	30	36.2 39.9 43.9	2.8 3.2 3.6(cell)
	Feng et al. (2018) [138]	24 cylindrical cells	2.6	–	–	0.5C 1C	25	< 39 < 50	–
	Ye et al. (2018) [139]	16 prismatic cells	18(cell)	flat heat pipe with fins		1C	28	< 35	1.5
Liquid cooling	Rao et al. (2013) [132]	2 electric heater (instead of rectangular cells)	–	4 copper tube heat pipe with flat shape in evaporation section	water	50 W 30 W	–	48 < 40(cell)	< 8.5 < 5
	Rao et al. (2014) [140]	2 electric heater (instead of rectangular cells)	–	4 turn oscillating copper tube heat pipe	acetone	20 W 25 W 30 W 35 W	–	51.01 58.38 63.59 67.69	1158s 710 s 560 s 110 s (time to reach 5 °C)
	Wang et al. (2015) [141]	2 Electric heater (instead of cells)	–	L-shape copper tube heat pipe with flat shape in evaporation section	water	Scenario 1 88.04 W (10 s) 41.27 W (900 s) 5.5 W (1800 s) Scenario 2 11.92 W (1800 s) 5.5 W(1800 s)	35	< 63 < 41	–
	Zhao et al. (2015) [136]	4 prismatic cells(4S1P)	3 8	aluminum flat heat pipe	acetone	3C	24.85	31.8	1.5(cell) 6.2(pack)
	Liang et al. (2018) [142]	2 prismatic cells	–	4 tubular heat pipe with flat shape flat shape in evaporation section		40–100 W	15 35	< 50 < 55	< 10(pack) < 6

performance and minimize the size and cost of system [131]. The results showed that the cell temperature gradient was decreased by increasing the PCM thickness and convective heat transfer coefficient. In addition, when the PCM was under natural convection conditions, the temperature continuously rose after the completion of the phase change due to the poor heat dissipation. As a result of summarizing previous studies, it has shown that using PCM in BTMS can effectively manage battery heat while reducing energy consumption. However, these studies are obtained without various analyzing the secondary PCM cooling effect under very small battery capacity and simple battery operating conditions. Therefore, it is necessary to study the PCM BTMS considered the effect of secondary PCM cooling in a large capacity battery and various conditions.

4.2. Heat pipe cooling system

The PCM cooling system mentioned above was able to lower the temperature of the battery without consuming energy due to the use of latent heat, but due to its low conductivity which results in inadequate temperature gradients and longtime response, it has difficulties to apply to BTMS. There have been many efforts to improve the thermal conductivity of many PCMs, but volume changes during the re-solidification process are difficult to manage. As a way to overcome these disadvantages, thermal management of the battery using a heat pipe may be a promising alternative. A heat pipe is a device that can operate spontaneously without external pumped power and transport large amounts of heat energy at considerable distances with high speeds utilizing phase-change heat transfer even at very small temperature differences. It also has features such as compact structure, flexible geometry, long lifetime and low maintenance, so that this has used in many industries for efficient thermal management . However, the heat pipe is not yet applied to the main purpose of actual EVs BTMS because of their low capacity and efficiency and small contact area. The structure of the heat pipe consists of only an airtight container and a working fluid. In detail, it is composed of an evaporator section, an adiabatic section and a condenser section. The evaporator section is attached to a heat source that needs cooling. The working fluid in a heat pipe evaporates by absorbing heat from the heat source and then moved to the condenser section through the adiabatic section due to the difference in internal pressure of the container. In the condenser section, the working fluid condenses through external heat exchange. After that, it has become liquid and moves back to the evaporator section by the capillary force of the wick. There are various kinds of methods in which the working fluid returns from the condenser section to the evaporator section depending on the driving force [117]. This series of processes can be repeated without external energy consumption. Fig. 2 (f) shows a schematic diagram of the heat pipe cooling system. Heat pipes are usually complex in shape, but in this figure, flat heat pipes are represented for simplicity. The heat pipes contact with the battery cells in order to cool the heat of the cells by conductive heat transfer. However,

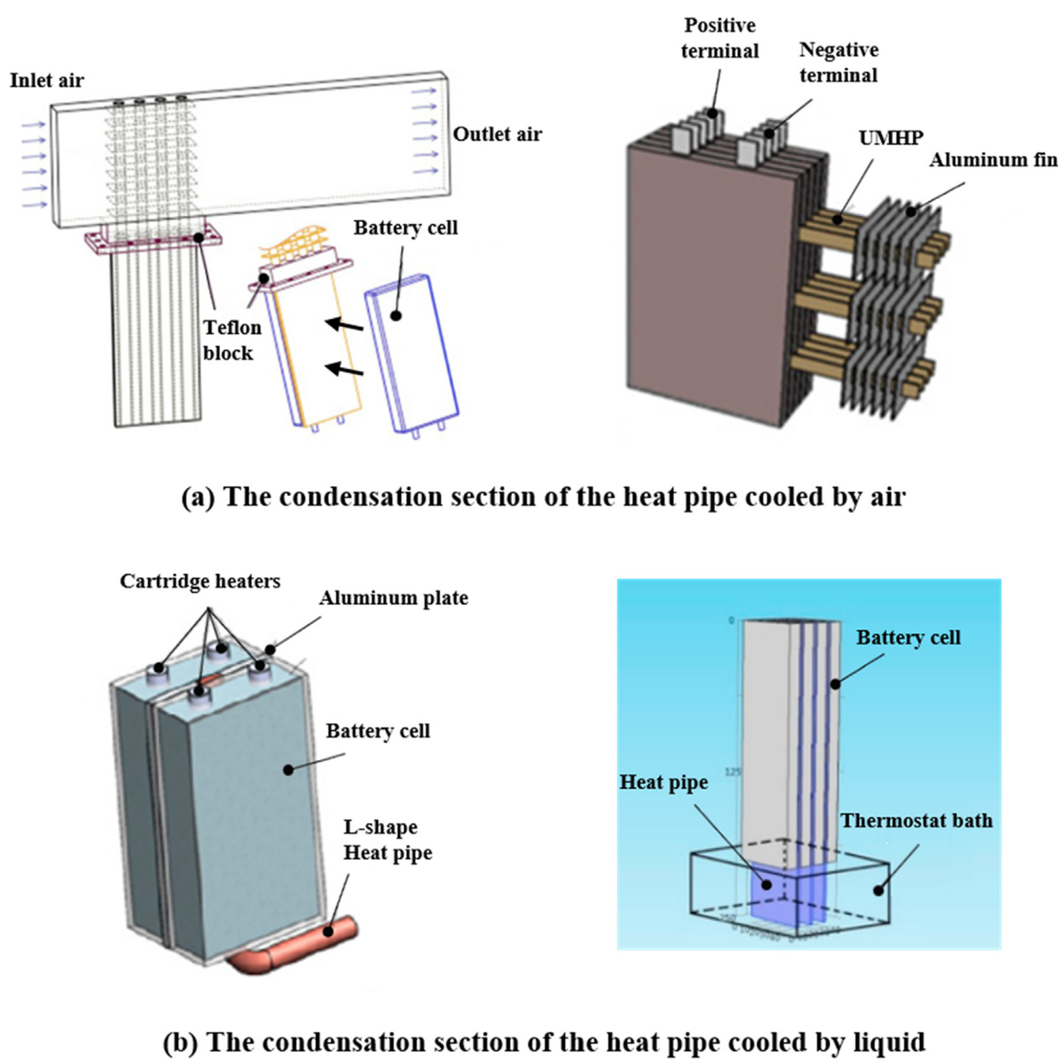

Fig. 7. Schematic diagrams of heat pipe cooling system [135-137,141].

since the available contact area of the heat pipes is limited, the heat pipes are inserted into the cooling plate having excellent thermal conductivity. Thus, heat pipe is often used for prismatic or pouch cells. When the battery is heated, the evaporator section of the heat pipe coupled with the cooling plate absorbs the heat of the battery through conduction and can be cooled through the outside air or liquid in the condenser section stretched to the end on the cooling plate. Table 5 shows the related researches of heat pipe cooling system. These studies can be classified as air cooling and liquid cooling depending on the cooling medium used for the cooling end of the heat pipe. Wu et al. (2002) investigated the thermal behavior of Li-ion batteries with natural convection, forced convection and heat pipe battery cooling systems by differentiating the state of charge and discharge current when discharging [133]. They considered heat pipe cooling system because forced convection cools battery heat more efficiently than natural convection, but temperature distribution is not uniform. As a result, the method of cooling of heat pipe lowered the surface temperature of the battery by 32 °C and the temperature distribution was also appropriate. Tran et al. (2014) compared the thermal performance of the cylindrical cells with a heat pipe cooling system and a natural/forced air convection cooling system and compared the thermal performance of the flat heat pipe cooling system by varying the positions [134]. Test results showed that heat pipes are 30% lower in thermal resistance than natural convection and 20% lower than forced convection when the air velocity is slow. They also studied the thermal behavior of tube heat pipes in various inclined positions, natural cooling and chimney cooling at condenser section. The study showed that natural convection cooling in the condenser section was not sufficient enough to maintain the proper temperature of the battery and the chimney ventilation method was effective in the heat release but was not suitable for the appropriate level of thermal performance at high load. Ye et al. (2015) investigated the cooling performance of a heat pipe cooling system using an additional copper heat sink and cooling fins to quickly charge the Li-ion battery [135]. Numerical simulations result of their system with forced air convection cooling emphasized that heat dissipation performance was improved with the aid of cooling fins, which enabled effective battery thermal management at the cell level, but not at the pack level. Zhao et al. (2015) compared the thermal behavior of Li-ion batteries using four different evaporator cooling type of heat pipe cooling systems under various automatic conditions [136]. According to the results of the study, the heat pipe cooling system with a combination of air cooling and wet cooling for cooling the condenser section of heat pipe at the 3C discharge rate was the best method with distribution of 1.2 °C and T_{max} of 21 °C. Liu et al. (2016) considered a system that uses an ultra-thin micro heat pipe (UMHP) to cool the battery to mitigate the temperature rise of a prismatic Li-ion battery pack with 5 parallel cells for EV [137]. They compared natural convection and forced air convection cooling systems to cool the condenser part of heat pipes at various discharge rates. As a result, the combined system of UMHP and natural convection cooling has difficulty in maintaining the proper operating temperature of the battery due to the possible dry-out phenomenon. Therefore, they proposed that forced convection cooling should be applied to cool the heat pipe in order to have better battery cooling performance. The schematics of the system applied by Ye et al. (2015) and Liu et al. (2016) is shown in Fig. 7(a). The heat pipe cooling system is used mostly on prismatic battery because of its handiness, but Feng et al. (2018) investigated the temperature and strain of cylindrical Li-ion battery by using a heat pipe cooling device with fan system [138]. It showed that when the heat pipe is cooled by natural convection, the battery cannot be adequately cooled at the end of the discharge process. However, when the heat pipe is cooled with air using a fan, the temperature of the entire pack was maintained to meet the operating temperature range with low energy consumption and the strain also decreased. Heat transfer efficiency of traditional circular heat pipes is low, because of the small contact area between the pipe surface and the battery. To overcome these drawbacks, Ye et al. (2018) applied flat micro-heat pipe arrays in Li-ion battery packs and investigated the cooling performance during the charge-discharge cycle [139]. The study showed that the use of the flat micro-heat pipe can save space and reduce system weight. In addition, they stated that it is possible to enhance the heat transfer rate when forced air convection cooling is applied together. Rao et al. (2013) studied the heat pipe cooling system with a heat pipe evaporator in a thermostat bath with constant liquid temperature maintained as a way to improve battery performance and life cycle [132]. As a result, the T_{max} was controlled below 50 °C when the heat generation rate was lower than 50 W and T_{max} was below 5 °C at less than 30 W input power. They also designed and experimented an oscillating heat pipe (OHP) [140]. They studied the battery temperature rise and temperature differences by changing the position of the OHP. Studies have shown that when the battery terminals approach the condenser section of the OHP, the T_{max} of the battery is reduced and it is advantageous to place the OHP vertically rather than horizontally to reduce the reflow resistance. Wang et al. (2015) also studied a system in which the condenser section of the L-type heat pipe under the battery cells to remove the heat from the battery through the liquid and the evaporator portion of the L-shaped heat pipe are attached to the aluminum plate and inserted into each battery cell cavity [141]. The schematics of the systems applied by Wang et al. (2015) and Zhao et al. (2015) is shown in Fig. 7(b). This proposed system maintained the battery surface temperature below 40 °C when the battery thermal power was less than 10 W per cell and 20 to 40 W below 70 °C. Liang et al. (2018) experimentally investigated the effect of coolant flow rate, ambient temperature, coolant temperature and start-up time on the thermal performance of heat pipe cooling system that cools the condenser portion of a heat pipe to a liquid [142]. Their study showed that the thermal performance was slightly improved after increasing the coolant flow rate to specific values at various ambient temperatures and lowering the liquid temperature could improve the thermal performance.

4.3. Thermoelectric element cooling system

Research and development of thermoelectric element over the past decade has received much attention due to their potential applications in environmentally friendly energy and energy management [143]. Thermoelectric element applications can be divided into two different groups. One is the thermoelectric generator (TEG) based on the Seebeck effect to convert heat into electricity to use waste heat as an energy source [144-146]. The other the thermoelectric cooler (TEC) based on the Peltier effect to convert electricity into thermal energy to provide cooling and heating for a variety of items [147,148]. TEC is already used in the field of automotive applications such as the climate control of EVs and the cooling and heating of luxury automobile seats [149,150]. Therefore, it can also be applied to BTMS. TEC consists of a matrix of p-type and n-type semiconductors alternately between two thin ceramic wafers and uses the Peltier effect to create a heat flux between the junction of two different types of conductors by passing the current through the circuit consisting of the matrices [151]. A simplified schematic of the thermoelectric element cooling system using TEC is shown in Fig. 2(g). The top side of the TEC (cold end) is attached to the battery and the bottom side (hot end) is connected to the cooling plate through which a heat transfer medium such as air or liquid flows. When TEC is supplied with direct current (DC) from the power supply system, heat generated from the battery is transferred from top side to the bottom side, so that the top side gets colder and the battery cools down. The system can also heat the battery by reversing the direction of the DC to the TEC. Thus the thermoelectric element cooling system can control the temperature of the battery to an appropriate level by adjusting the direction and amount of the supplied DC. This system typically has the advantages of compact size and moderate weight, low maintenance effort, wide operating temperature range, high reliability, no mechanical moving parts, noiseless and long life [152]. Despite the advantages mentioned above, due to the low efficiency of the Peltier process, realistic application and research on automotive BTMS are not actively pursued.

A few studies on this system have been categorized and reviewed according to the fluid flowing through the cooling plate attached to the hot end. Studies using air as a fluid are as follows. Alaoui (2013) proposed BTMS using TEC combined with forced air cooling [153]. As shown in Fig. 8(a), which shows one cell unit in a 48-cell battery-cell thermal management system, they mounted six TEC modules coupled with the extruded heat sink on the surface of a 60Ah Li-ion pouch cell and screwed the cell onto the aluminum plate for mechanical support. In addition, they constructed four blowers next to the heat sink to discharge heat from the battery to the outside. Their proposed BTMS was evaluated for the energy consumption to maintain the proper temperature of the battery and coefficient of performance (COP) under 3C constant discharge current conditions and US06 drive cycle conditions. According to the research results, the proposed BTMS consumed 919 Wh to reduce the pack temperature from 57.6 °C (temperature when there is no BTMS) to 46.8 °C under 3C discharge conditions and 317 Wh in the drive cycle condition to lower 8.82 °C at the temperature without BTMS. In addition, the COP is about 0.9 for the constant current test and about 1.2 for the drive cycle. Esfahanian et al. (2013) have proposed a new way to improve air-cooled thermal management with the help of thermoelectric because air-cooled cooling does not effectively cool the battery at high discharge rates and under abusive conditions such as high operating temperatures or ambient temperatures [154]. They proposed a system that was numerically analyzed using a three-dimensional CFD model. Simulation results show that under high charge/discharge rate and ambient temperature above 40 °C, the battery temperature can be kept below 35 °C and the cell temperature difference below about 6 °C. On the other hand, studies using liquids to cool the hot end of TEC are as follows. Liu et al. (2014) proposed a new BTMS using TEC combined with liquid cooling [155]. They developed a thermal model of a Li-ion battery and TEC and calibrated the model through experiments. In the proposed BTMS, the cold end of the TEC is attached to the battery cells to absorb their heat, and the hot end is attached to the water jacket to transfer heat. They firstly developed a thermal model of TEC and battery, then analyzed the cooling performance of the proposed system applied to the battery pack consisting of eight cells with 100Ah capacity. Simulation results at 1C discharge conditions showed that the TEC cooling allowed the battery temperature to remain below 40 °C and the average temperature difference between battery cells was less than 1 °C. These results are much better than cooling without TEC. However, the TEC has a small contact area between the batteries, which increases the uneven temperature in the battery cell. To overcome these problems, they argued that it can be overcome by inserting a high conductivity material between the TEC. Troxler et al. (2014) studied the effect of artificially induced temperature gradient on cell performance [156]. They used TEC to induce and maintain the temperature gradient of the Li-ion battery at isothermal and non-isothermal conditions, not battery cooling. However, their experimental setup shown in Fig. 8 (b) shows how to apply the TEC to cool the battery. One side of the TEC is in contact with the copper plate to increase the contact area with the battery cell and the other side is attached to the heat sink through which the cooling water flows to discharge the heat transmitted by the copper plate.

5. Discussion

Throughout the review, it was found that it was difficult to compare each system quantitatively due to the difference in battery type, capacity, charge/discharge rate and other external conditions. Thus, it would be helpful to evaluate several BTMSs under the same conditions to thoroughly understand the thermal characteristics of each system. Among the BTMS using the VCC, the cabin air cooling system has a simple structure using the air, which is advantageous in terms of cost, maintenance and reliability, but has relatively low cooling performance due to low heat transfer coefficient of air. As a result, this system is suitable for short-distance EVs with low battery capacity and low battery heat load. In order to cope with a large battery heat load, a large amount of air flow rate is needed, demanding high fan power consumption and broad space which is a fatal drawback to the vehicle. Recently, the secondary loop liquid cooling system has been widely used in EVs. This system has better cooling performance than cabin air cooling because the liquid has a higher heat transfer coefficient than air. Compared to the cabin air cooling system, it needs more components, which have disadvantages in terms of cost, reliability, maintenance, and coolant leakage. The direct refrigerant two-phase cooling system is used to overcome previous BTMSs. This system can provide a larger heat transfer performance by using two phase heat transfer. In addition, since latent heat transfer is applied, heat can be exchanged at uniform temperature. This can increase battery temperature uniformity. Moreover, this system reduces the complexity of the system by eliminating some additional components, which can improve the reliability. However, more refrigerant has to be charged, which may increase the direct greenhouse gas emission (it depends on the global warming potential of the refrigerant). Among the BTMSs that do not use the VCC, the PCM cooling system showed promising results and high performance in thermal management due to the ability of containing high latent heat. However, since it takes time to re-solidify the PCM, it cannot continuously respond to the thermal load of the battery. Also, there is a problem of volume change and electrical conductivity. The heat pipe cooling system is a passive thermal management system, which is hard to actively control the temperature, but it does not

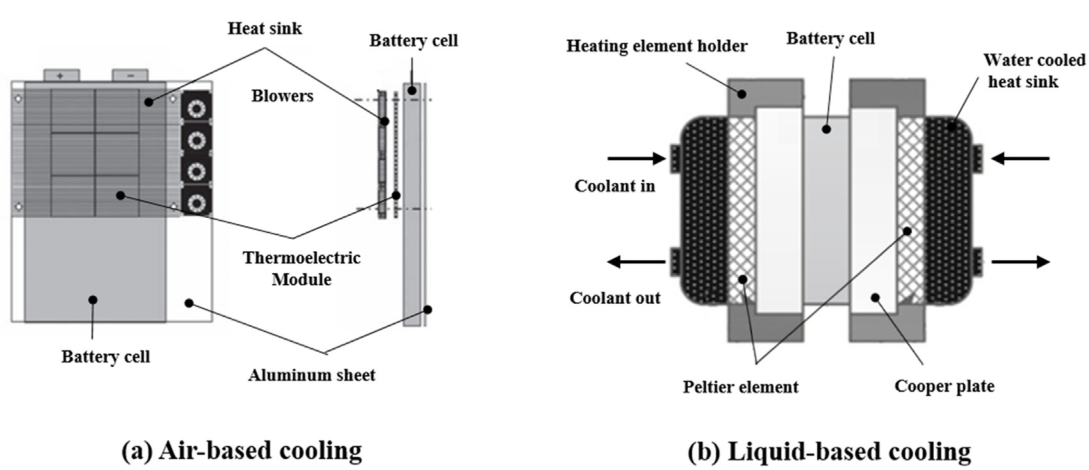

Fig. 8. Schematic diagrams of thermoelectric elements cooling [153,156].

consume much power. Lastly, thermoelectric cooling systems can control the temperature accurately but consume relatively large power due to the low efficiency.

The requirements for battery use in EVs may vary depending on the type of vehicles [157]. EVs need the largest amount of energy with the smallest possible weight to increase mileage. Therefore, the energy and power density of Li-ion batteries are expected to be improved in the future. The trend of the energy density increase in Li-ion batteries is shown in Fig. 9 [158]. Although this trend indicates future increase of the EVs' mileage, more serious thermal challenges can occur due to abnormal heat emissions and heat accumulation. Each BTMS reviewed in this paper has advantages and disadvantages, and there are limitations for the application to the high energy density batteries. Therefore, studies to combine BTMSs have been paid attention, which can amplify the advantages and reduce the disadvantages of each system. These studies are summarized in Table 6. Wu et al. (2017) recently analyzed the thermal performance of a heat pipe-assisted PCM based BTM [159]. Their experimental results showed that the proposed system is effective and feasible for EV and HEV by observing considerable temperature reduction at high discharge rate and having relatively long operating time at 50 °C. Zhao et al. (2017) designed and experimentally studied the PCM/heat pipe coupled thermal management system for battery module of cylindrical cells [123]. Their study showed that PCM/heat pipe coupled BTMS maintained a T_{max} of 50 °C and a ΔT_{max} of less than 5 °C longer than the air-based, PCM-based system at the same conditions. Yamada et al. (2017) also developed a hybrid cooling system coupled with PCM and heat pipes to control the abnormal heat generation that occurs as the energy and power density of the battery increases [160]. The proposed system took 708 s, which took the longest time, to reach the critical temperature of 80 °C leading to thermal runaway. Wang et al. (2016) experimentally studied a PCM/OHP-based BTMS instead of the previously used flat heat pipe [161]. Rao et al. (2016) proposed a BTMS combined with PCM and liquid-flow minichannel and discussed various influencing factors such as phase transition temperature, PCM thermal conductivity, channel number and mass flow rate through simulation of a 3D battery thermal model [162]. Wei and Agelin-Chaab (2018) experimentally investigated BTMS that constitute a series of hydrophilic fiber channels containing a water coolant to extract the latent heat of the battery into the ducts of air cooling system [163]. These studies did not have much research on applying realistic batteries and were studied in specific capacity battery cells. Therefore, in the future, it is necessary to analyze the cooling performance in the module and pack unit applied to real EV. In addition, cost, weight and size of the BTMS must be taken into consideration for application to the EV.

As a combined system to minimize energy consumption, system weight and maximize thermal performance of high energy-dense batteries, a novel cell-based BTMS is proposed, which is named as an integrated phase change heat transfer package (IHP) [164]. This system combines the direct refrigerant two-phase cooling system, heat pipe cooling system and PCM cooling system. A schematic diagram of this system is shown in Fig. 10. In this system, the OHP is directly attached to the battery cell to disperse the heat of the high-temperature part of the cell to the low-temperature part without energy consumption for temperature uniformity. As the temperature of the cell gradually increases after the temperature becomes uniform, the battery heat is discharged to the outside through the two-phase heat transfer of the refrigerant flowing in the roll-bond heat exchanger thinner than conventional heat exchanger. Lastly, a PCM composite is constructed between OHP and roll-bond heat exchanger to reduce thermal resistance and serve a thermal buffer role in the idling state of the vehicle. This proposed system is expected to reduce the energy consumption and system size and have a large cooling power and uniform temperature distribution. In the future, constructing and testing the proposed system to analyze the performance should be conducted and studies that complement the weak points of each BTMS by combining each system should be actively executed.

6. Conclusions

For EVs, the effective BTMS is necessary to improve the performance and safety. This paper extensively reviews and classifies the existing BTMS studies according to its thermal cycle options. BTMS with the VCC is subdivided into cabin air cooling system, secondary loop liquid cooling system and direct refrigerant two-phase cooling system. On the other hand, BTMS without the VCC is categorized as PCM cooling system, heat pipe cooling system and thermoelectric element cooling system. BTMS using VCC has been applied to most of the EVs because of its advantage of utilizing existing AC systems to cool or heat the battery. However, it consumes a large amount of energy to drive some devices such as compressors, fans and pumps and commonly affects cabin air conditioning. To be more specific, the cabin air cooling system has the advantage of system simplicity of low weight, cost and maintenance, but this system has the problems of low cooling performance due to the low heat capacity of the air, fan noise problems and limited space utilization. In order to achieve higher cooling performance in this system, there have been many studies related to geometric optimization such as air channels, cell configuration and air flow paths. Secondary liquid loop cooling systems can be more efficient in cooling performance than cabin air cooling systems because they use liquid with higher heat capacity than air. However, this system also has the disadvantage of increased complexity, price and weight due to the addition of heat exchangers and circuit. The direct refrigerant two-phase cooling system uses two-phase heat exchanging of refrigerants, which in result has a better cooling performance at low mass flow rate than secondary liquid loop cooling systems that perform single phase heat exchanging. In addition, the system can reduce complexity and weight by eliminating the need for liquid circuits and additional heat exchangers. However, this system has a problem that the VCC has to operate to cool the battery.

Although BTMS without the VCC is not widely applied to actual EVs, it still has a great potential in terms of energy consumption and thermal performance. The PCM cooling systems are capable of absorbing a large amount of battery heat at the same temperature in a phase change process with little or no energy consumption. However, this system has problems in coping with the low thermal conductivity of PCM, continuous battery heat load after completion of phase change of PCM, leakage of PCM, volume change and inhomogeneity of the whole module in repeated melting/solidifying processes. The heat pipe cooling system can transfer heat more efficiently due to the higher thermal conductivity of the heat pipe than general PCM, but it is required to combine with a cooling plate because of the limited contact area with the battery. Thermoelectric element cooling system can control the temperature of the battery precisely by controlling the

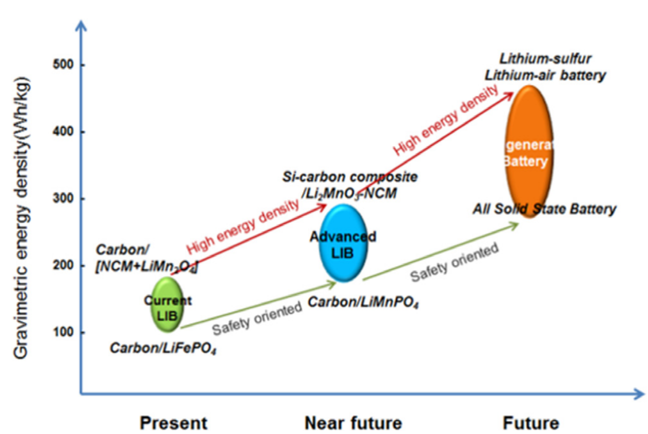

Fig. 9. Status and prospects of automotive next generation battery [158].

Table 6
Summary of studies of combined battery cooling system.

Combination	Author (Year)	Li-ion Battery	Battery capacity (Ah)	Heat pipe (working fluid)	PCM and thermal conductivity ($W{\cdot}m^{-1}K^{-1}$)	Battery load	T_{max} (°C)	ΔT_{max} (°C)
PCM and Heat pipe	Wu et al. (2017) [159]	5 prismatic cells	12	2 flat L-shape copper heat pipe (water)	Paraffin/EG (7.654)	1C 3C 5C	< 30 42.8 50.9	< 1 < 1 < 2
	Yamada et al. (2017) [160]	Heater		20 flat shape heat pipe(water)	RT50(0.2)	400 W	44.3 (60 s)	–
PCM and Heat pipe with forced air convection cooling	Wu et al. (2017) [159]	5 prismatic cells	12	2 flat L-shape copper heat pipe (water)	Paraffin/EG (7.654)	5C	49.4	–
	Zhao et al. (2017) [123]	Heater	–	6 copper heat pipe	Paraffin/EG composite	5–15 W	< 50 (611 s)	< 5 (620 s)
PCM and Heat pipe with liquid cooling	Wang et al. (2016) [161]	Heater	–	Oscillating copper heat pipe	Paraffin (solid 0.21, liquid 0.29)	20 W 25 W 30 W	44.62 48.86 55.56	850 s 178 s 96 s(time to reach 5 °C)
PCM and liquid cooling	Rao et al. (2016) [162]	–	–	–	(0.2–2)	5C	47.45	< 6
Forced air cooling and liquid cooling with coil channel	Wei and Chaab (2018) [163]	1	5.2	–	–	< 0.2C(charging) 1.15C(discharging)	30.5	2.1

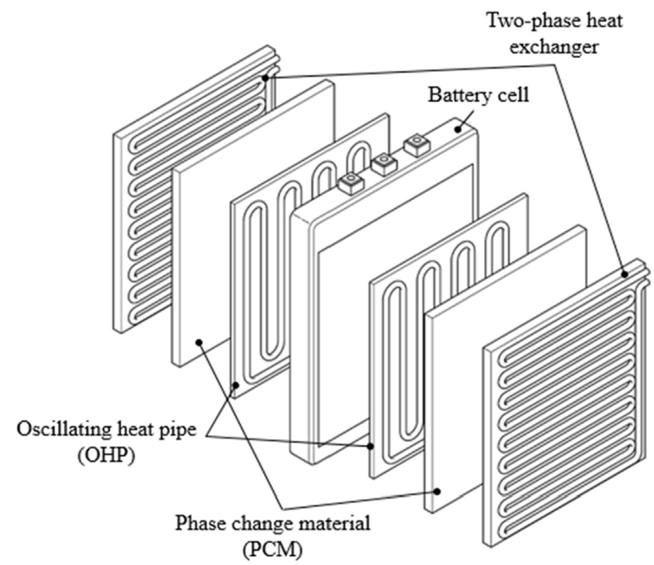

Fig.10. Integrated phase change heat transfer package (IPH) [164].

amount and direction of the current in the TEC. However, since its efficiency is very poor, in-depth studies have not been conducted yet.

As a result of reviewing various BTMS, it was found that the comparison of each system was not directly comparable due to the difference of type, capacity, and operating conditions of the tested batteries. However, the advantages and disadvantages of each system were identified. Therefore, in order to develop a more effective BTMS, it is crucial to select an appropriate BTMS depending on the purpose of the EV and combining various systems to compensate for the disadvantages.

In the future, thermal load of the EV batteries is expected to increase due to the increased energy density of the battery. Therefore, the BTMS will be developed to integrate several BTMS options, such as the direct two-phase refrigerant cooling with the PCM, heat pipe and thermoelectric systems.

Acknowledgement

This research was supported by the Energy Efficiency & Resources Core Technology Program of the Korea Institute of Energy Technology Evaluation and Planning (KETEP), funded by the Ministry of Trade, Industry & Energy, Republic of Korea. (No. 2018201060010B).

References

[1] International Energy Agency. https://www.iea.org/publications/freepublications/publication/GlobalEVOutlook2017.pdf [accessed 2018-02-27].
[2] H.P.J. De Wilde, P. Kroon, Policy options to reduce passenger cars CO2 emissions after 2020.ECN. ECNE13005 2013.
[3] S. Oberthür, The new climate policies of the European Union: internal legislation and climate diplomacy, ASP/VUBPRESS/UPA (2010).
[4] B. Dunn, H. Kamath, J.M. Tarascon, Electrical energy storage for the grid: a battery of choices, Science 334 (2011) 928–935.
[5] S.M. Lukic, J. Cao, R.C. Bansal, F. Rodriguez, A. Emadi, Energy storage systems for automotive applications, IEEE Trans. Ind. Electron. 55 (2008) 2258–2267.
[6] H. Budde Meiwes, J. Drillkens, B. Lunz, J. Muennix, S. Rothgang, J. Kowal, D.U. Sauer, A review of current automotive battery technology and future prospects, Automobile Eng. 227 (2013) 761–776.
[7] S.M.A.S. Bukhari, J. Maqsood, M.Q. Baig, S. Ashraf, T.A. Khan, Comparison of Characteristics-Lead Acid, Nickel Based, Lead Crystal and Lithium Based Batteries, IEEE Modelling and Simulation (UKSim), 2015.
[8] M. Lowe, S. Tokuoka, T. Trigg, G. Gereffi, Lithium-ion batteries for electric vehicles, Duke University Center on Globalization, Governance and Competitiveness, Tech. Rep., 2010.
[9] J.M. Tarascon, M. Armand, Issues and challenges facing rechargeable lithium batteries. In Materials For Sustainable Energy. A Collection of Peer-Reviewed Research and Review Articles from Nature Publishing Group 2011. p. 171-179.
[10] T. Sasaki, Y. Ukyo, P. Novák, Memory effect in a lithium-ion battery, Nat. Mater.

12 (2013) 569.
[11] V. Etacheri, R. Marom, R. Elazari, G. Salitra, D. Aurbach, Challenges in the development of advanced Li-ion batteries: a review, Energy Environ. Sci. 4 (2011) 3243–3262.
[12] T.M. Bandhauer, S. Garimella, T.F. Fuller, A critical review of thermal issues in lithium-ion batteries, Electrochem. Soc. 158 (2011) R1–R25.
[13] K. Smith, C.Y. Wang, Power and thermal characterization of a lithium-ion battery pack for hybrid-electric vehicles, Power Sources 160 (2006) 662–673.
[14] A.A. Pesaran, Battery thermal management in EV and HEVs: issues and solutions, Battery Man 43 (2001) 34–49.
[15] Pesaran AA., Santhanagopalan S, Kim GH. Addressing the impact of temperature extremes on large format li-ion batteries for vehicle applications (presentation). No. NREL/PR-5400-58145. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2013.
[16] A.A. Pesaran, Battery thermal models for hybrid vehicle simulations, Power Sources 110 (2002) 377–382.
[17] Q. Wang, B. Jiang, B. Li, Y. Yan, A critical review of thermal management models and solutions of lithium-ion batteries for the development of pure electric vehicles, Renew. Sustain. Energy Rev. 64 (2016) 106–128.
[18] Z. Rao, S. Wang, A review of power battery thermal energy management, Renew. Sustain. Energy Rev. 15 (2011) 4554–4571.
[19] M.R. Cosley, M.P. Garcia, Battery thermal management system. Telecommunications Energy Conference, 2004. INTELEC 2004. 26th Annual International. IEEE, 2004.
[20] D. Pan, S. Xu, C. Lin, G. Chang, Thermal management of power batteries for electric vehicles using phase change materials, A Review, SAE Technical Paper (2016–01-1204.).
[21] H. Liu, Z. Wei, W. He, J. Zhao, Thermal issues about Li-ion batteries and recent progress in battery thermal management systems:a review, Energy Convers. Manage. 150 (2017) 304–330.
[22] G. Xia, L. Cao, G. Bi, A review on battery thermal management in electric vehicle application, Power Sources 367 (2017) 90–105.
[23] J. Larminie, J. Lowry, Electric vehicle technology explained, John Wiley & Sons, 2012.
[24] S. Al Hallaj, H. Maleki, J.S. Hong, J.R. Selman, Thermal modeling and design considerations of lithium-ion batteries, Power Sources 83 (1999) 1–8.
[25] K.E. Thomas, J. Newman, Thermal modeling of porous insertion electrodes, Electrochem. Soc. 150 (2003) A176–A192.
[26] W.B. Gu, C.Y. Wang, Thermal-electrochemical modeling of battery systems, Electrochem. Soc. 147 (2000) 2910–2922.
[27] A. Fotouhi, D.J. Auger, K. Propp, S. Longo, M. Wild, A review on electric vehicle battery modelling: from Lithium-ion toward Lithium-Sulphur, Renew. Sustain. Energy Rev. 56 (2016) 1008–1021.
[28] N. Baba, H. Yoshida, M. Nagaoka, C. Okuda, S. Kawauchi, Numerical simulation of thermal behavior of lithium-ion secondary batteries using the enhanced single particle model, Power Sources 252 (2014) 214–228.
[29] P. Peng, F. Jiang, Thermal safety of lithium-ion batteries with various cathode materials: a numerical study, Heat Mass Transf. 103 (2016) 1008–1016.
[30] X. Lin, H.E. Perez, S. Mohan, J.B. Siegel, A.G. Stefanopoulou, Y. Ding, M.P. Castanier, A lumped-parameter electro-thermal model for cylindrical batteries, Power Sources 257 (2014) 1–11.
[31] E. Martínez-Rosas, R. Vasquez-Medrano, A. Flores-Tlacuahuac, Modeling and simulation of lithium-ion batteries, Comput. Chem. Eng. 35 (2011) 1937–1948.
[32] A. Samba, N. Omar, H. Gualous, Y. Firouz, P. Van den Bossche, J. Van Mierlo, T.I. Boubekeur, Development of an advanced two-dimensional thermal model for large size lithium-ion pouch cells, Electrochim. Acta 117 (2014) 246–254.
[33] M. Guo, G.H. Kim, R.E. White, A three-dimensional multi-physics model for a Li-ion battery, Power Sources 240 (2016) 80–94.
[34] T. Joshi, Capacity and power fade in lithium-ion batteries, PhD Thesis. Georgia Institute of Technology (2016).
[35] G.M. Ehrlich, Lithium-ion batteries. Handbook of batteries, 2002.35-53.
[36] P. Ramadass, B. Haran, R. White, B.N. Popov, Capacity fade of Sony 18650 cells cycled at elevated temperatures: Part I. Cycling performance, J. Power Sources 112 (2002) 606–613.
[37] J. Shim, R. Kostecki, T. Richardson, X. Song, K.A. Striebel, Electrochemical analysis for cycle performance and capacity fading of a lithium-ion battery cycled at elevated temperature, J. Power Sources 112 (2002) 222–230.
[38] K. Amine, J. Liu, I. Belharouak, High-temperature storage and cycling of C-LiFePO 4/graphite Li-ion cells, Electrochem. Commun. 7 (2005) 669–673.
[39] P. Liu, J. Wang, J. Hicks-Garner, E. Sherman, S. Soukiazian, M. Verbrugge, H. Tataria, J. Musser, P. Finamore, Aging mechanisms of LiFePO4 batteries deduced by electrochemical and structural analyses, J. Electrochem. Soc. 157 (2010) A499–A507.
[40] J. Jaguemont, L. Boulon, P. Venet, Y. Dubé, A. Sari, Lithium-ion battery aging experiments at subzero temperatures and model development for capacity fade estimation, IEEE Trans. Veh. Technol. 65 (2016) 4328–4343.
[41] Y. Zheng, Y.B. He, K. Qian, D. Liu, Q. Lu, B. Li, X. Wang, J. Li, F. Kang, Influence of charge rate on the cycling degradation of LiFePO4/mesocarbon microbead batteries under low temperature, Ionics (2017) 1–12.
[42] J.R. Belt, C.D. Ho, T.J. Miller, M.A. Habib, T.Q. Duong, The effect of temperature on capacity and power in cycled lithium ion batteries, Power Sources 142 (2005) 354–360.
[43] Q. Wang, P. Ping, X. Zhao, G. Chu, J. Sun, C. Chen, Thermal runaway caused fire and explosion of lithium ion battery, Power Sources 208 (2012) 210–224.
[44] A. Hammami, N. Raymond, M. Armand, Lithium-ion batteries: runaway risk of forming toxic compounds, Nature 424 (2003) 635–636.
[45] P.G. Balakrishnan, R. Ramesh, T.P. Kumar, Safety mechanisms in lithium-ion batteries, Power Sources 155 (2006) 401–414.
[46] P.C. Bhatia, Thermal analysis of lithium-ion battery packs and thermal management solutions, PhD Thesis The Ohio State University, 2013.
[47] N. Yang, X. Zhang, B. Shang, G. Li, Unbalanced discharging and aging due to temperature differences among the cells in a lithium-ion battery pack with parallel combination, Power Sources 306 (2016) 733–741.
[48] J. Wu, B, V. Yufit, M. Marinescu, G.J. Offer, R.F. Martinezbotas, N.P. Brandon, Coupled thermal–electrochemical modelling of uneven heat generation in lithium-ion battery packs, Power Sources 243 (2013) 544–554.
[49] Muratori, M. Thermal characterization of Lithium-ion battery cell. 2010.
[50] X. Feng, M. Ouyang, X. Liu, L. Lu, Y. Xia, X. He, Thermal runaway mechanism of lithium ion battery for electric vehicles: a review, Energy Storage Mater. 10 (2018) 246–267.
[51] Y. Ji, Low-temperature operation of Li-ion batteries for hybrid and electric vehicles. The Pennsylvania State University, 2014.
[52] M.C. Smart, B.V. Ratnakumar, S. Surampudi, Y. Wang, X. Zhang, S.G. Greenbaum, B. Fultz, Irreversible capacities of graphite in low-temperature electrolytes for lithium-ion batteries, Electrochem. Soc. 146 (1999) 3963–3969.
[53] H.C.A. Shiao, D. Chua, H.P. Lin, S. Slane, M. Salomon, Low temperature electrolytes for Li-ion PVDF cells, Power sources 87 (2000) 167–173.
[54] S.S. Zhang, K. Xu, T.R. Jow, The low temperature performance of Li-ion batteries, Power Sources 115 (2003) 137–140.
[55] J. Fan, On the discharge capability and its limiting factors of commercial 18650 Li-ion cell at low temperatures, Power Sources 117 (2003) 170–178.
[56] J. Fan, S. Tan, Studies on charging lithium-ion cells at low temperatures, Electrochem. Soc. 153 (2006) A1081–A1092.
[57] C. Wang, A.J. Appleby, F.E. Little, Low-temperature characterization of lithium-ion carbon anodes via microperturbation measurement, Electrochem. Soc. 149 (2002) A75460.
[58] T.A. Stuart, A. Hande, HEV battery heating using AC currents, Power Sources 129 (2004) 368–378.
[59] C. Alaoui, Z.M. Salameh, A novel thermal management for electric and hybrid vehicles, IEEE Trans. Veh. Technol. 54 (2) (2005) 468–476.
[60] J. Li, P. Wu, H. Tian, Researches on heating low-temperature lithium-ion power battery in electric vehicles. In Transportation Electrification Asia-Pacific (ITEC Asia-Pacific), In: 2014 IEEE Conference and Expo (pp. 1-6).
[61] L.E.I. Zhiguo, C. Zhang, L.I. Junqiu, F.A.N. Guangchong, L.I.N. Zhewei, Preheating method of lithium-ion batteries in an electric vehicle, Modern Power Syst. Clean Energy 3 (2015) 289–296.
[62] D. Adair, K. Ismailov, Z. Bakenov, Thermal Management of Lithium-ion, Battery Packs. (2014).
[63] M.R. Khan, M.J. Swierczynski, S.K. Kær, Towards an ultimate battery thermal management system: a review, Batteries 3 (2017) 9.
[64] A. Pesaran, M. Keyser, S. Burch, An approach for designing thermal management systems for electric and hybrid vehicle battery packs, National Renewable Energy Laboratory, Golden, CO (US), 1999.
[65] R. Sabbah, R. Kizilel, J.R. Selman, S. Al-Hallaj, Active (air-cooled) vs. passive (phase change material) thermal management of high power lithium-ion packs: Limitation of temperature rise and uniformity of temperature distribution, Power Sources 182 (2008) 630–638.
[66] H. Teng, Yeow K. Design of direct and indirect liquid cooling systems for high-capacity, high-power lithium-ion battery packs, 1(2012–01-2017), Alternative Powertrains (2012) 525–5360.
[67] H. Zou, B. Jiang, Q. Wang, C. Tian, Y. Yan, Performance analysis of a heat pump air conditioning system coupling with battery cooling for electric vehicles, Energy Procedia 61 (2014) 891–894.
[68] B. Scrosati, J. Garche, W. Tillmetz, Advances in battery technologies for electric vehicles, Woodhead Publishing, 2015.
[69] K. Chen, Z. Li, Y. Chen, S. Long, J. Hou, M. Song, S. Wang, Design of parallel air-cooled battery thermal management system through numerical study, Energies 10 (2017) 1677.
[70] C. Huber, R. Kuhn, Thermal management of batteries for electric vehicles, Adv. Battery Technol. Electric Vehicles (2015) 327–358.
[71] G.H. Kim, A.A. Pesaran, Battery thermal management system design modeling. National Renewable Energy Laboratory. 2006.
[72] H. Park, A design of air flow configuration for cooling lithium ion battery in hybrid electric vehicles. power sources 2013;239:30-6.
[73] X.M. Xu, R. He, Research on the heat dissipation performance of battery pack based on forced air cooling, Power Sources 240 (2013) 33–41.
[74] H. Sun, R. Dixon, Development of cooling strategy for an air cooled lithium-ion battery pack, Power Sources 272 (2014) 404–414.
[75] K. Chen, S. Wang, M. Song, L. Chen, Structure optimization of parallel air-cooled battery thermal management system, Heat Mass Transf. 111 (2017) 943–952.
[76] J. Xie, Z. Ge, M. Zang, S. Wang, Structural optimization of lithium-ion battery pack with forced air cooling system, Appl. Therm. Eng. 126 (2017) 583–593.
[77] S. Hong, X. Zhang, K. Chen, S. Wang, Design of flow configuration for parallel air-cooled battery thermal management system with secondary vent, Heat Mass Transf. 116 (2018) 1204–1212.
[78] L. Fan, J.M. Khodadadi, A.A. Pesaran, A parametric study on thermal management of an air-cooled lithium-ion battery module for plug-in hybrid electric vehicles, Power Sources 238 (2013) 301–312.
[79] T. Wang, K.J. Tseng, J. Zhao, Z. Wei, Thermal investigation of lithium-ion battery module with different cell arrangement structures and forced air-cooling strategies, Appl. Energy 134 (2014) 229–238.
[80] T. Wang, K.J. Tseng, J. Zhao, Development of efficient air-cooling strategies for

lithium-ion battery module based on empirical heat source model, Appl. Therm. Eng. 90 (2015) 521–529.
[81] N. Yang, X. Zhang, G. Li, D. Hua, Assessment of the forced air-cooling performance for cylindrical lithium-ion battery packs: A comparative analysis between aligned and staggered cell arrangements, Appl. Therm. Eng. 80 (2015) 55–65.
[82] R. Mahamud, C. Park, Reciprocating air flow for Li-ion battery thermal management to improve temperature uniformity, Power Sources 196 (2011) 5685–5696.
[83] K. Yu, X. Yang, Y. Cheng, C. Li, Thermal analysis and two-directional air flow thermal management for lithium-ion battery pack, Power Sources 270 (2014) 193–200.
[84] Z. Lu, X.Z. Meng, L.C. Wei, W.Y. Hu, L.Y. Zhang, L.W. Jin, Thermal management of densely-packed EV battery with forced air cooling strategies, Energy Procedia 88 (2016) 682–688.
[85] Y.S. Choi, D.M. Kang, Prediction of thermal behaviors of an air-cooled lithium-ion battery system for hybrid electric vehicles, Power Sources 270 (2014) 273–280.
[86] J. Xun, R. Liu, K. Jiao, Numerical and analytical modeling of lithium ion battery thermal behaviors with different cooling designs, Power Sources 233 (2013) 47–61.
[87] C. Zhu, X. Li, L. Song, L. Xiang, Development of a theoretically based thermal model for lithium ion battery pack, J. Power Sources 223 (2013) 155–164.
[88] I.L. Krüger, D. Limperich, G. Schmitz, Energy consumption of battery cooling in hybrid electric vehicles. 2012.
[89] K. Rahman, S. Jurkovic, C. Stancu, J. Morgante, P. Savagian, Design and performance of electrical propulsion system of extended range electric vehicle (EREV) Chevrolet Voltec. In Energy Conversion Congress and Exposition (ECCE), 2012 IEEE (pp. 4152-4159).
[90] A. Jarrett, I.Y. Kim, Design optimization of electric vehicle battery cooling plates for thermal performance, Power Sources 196 (2011) 10359–10368.
[91] A. Jarrett, I.Y. Kim, Influence of operating conditions on the optimum design of electric vehicle battery cooling plates, Power Sources 245 (2014) 644–655.
[92] L.W. Jin, P.S. Lee, X.X. Kong, Y. Fan, S.K. Chou, Ultra-thin minichannel LCP for EV battery thermal management, Appl. Energy 113 (2014) 1786–1794.
[93] Y. Huo, Z. Rao, X. Liu, J. Zhao, Investigation of power battery thermal management by using mini-channel cold plate, Energy Convers. Manage. 89 (2015) 387–395.
[94] J. Zhao, Z. Rao, Y. Li, Thermal performance of mini-channel liquid cooled cylinder based battery thermal management for cylindrical lithium-ion power battery, Energy Convers. Manage. 103 (2015) 157–165.
[95] Z. Qian, Y. Li, Z. Rao, Thermal performance of lithium-ion battery thermal management system by using mini-channel cooling, Energy Convers. Manage. 126 (2016) 622–631.
[96] C. Lan, J. Xu, Y. Qiao, Y. Ma, Thermal management for high power lithium-ion battery by minichannel aluminum tubes, Appl. Therm. Eng. 101 (2016) 284–292.
[97] C. Wang, G. Zhang, L. Meng, X. Li, W. Situ, Y. Lv, M. Rao, Liquid cooling based on thermal silica plate for battery thermal management system, Energy Research 41 (2017) 2468–2479.
[98] S. Panchal, R. Khasow, I. Dincer, M. Agelin-Chaab, R. Fraser, M. Fowler, Thermal design and simulation of mini-channel cold plate for water cooled large sized prismatic lithium-ion battery, Appl. Therm. Eng. 122 (2017) 80–90.
[99] M. Malik, I. Dincer, M.A. Rosen, M. Mathew, M. Fowler, Thermal and electrical performance evaluations of series connected Li-ion batteries in a pack with liquid cooling, Appl. Therm. Eng. 129 (2018) 472–481.
[100] Z. Rao, Z. Qian, Y. Kuang, Y. Li, Thermal performance of liquid cooling based thermal management system for cylindrical lithium-ion battery module with variable contact surface, Appl. Therm. Eng. 123 (2017) 1514–1522.
[101] F. Schoewel, E. Hockgeiger, The High voltage batteries of the BMW i3 and i8 AABC 2014, February 3th- 7th, Atlanta. [accessed 2018-02-27].
[102] S. George, Keith Ritter Bower, http://www.hybridcars.com/bmw-and-lg-chem-trump-tesla-in-battery-thermal-management [accessed 2018-02-27].
[103] S. Ketkar, P. Laurain, R. McCormick, Battery system and method for cooling the battery system. U.S. Patent No. 9,379,420. 2016.
[104] Electric Vehicles in America. http://www.slideshare.net/ap3slidshare/alfred-piggott-20120531-battery-cooling-system-layout-thermal-management-thermal [accessed 2018-02-27].
[105] Carpenter, N. U.S. Patent No. 20120297809A1. Washington, DC: U.S. Patent and Trademark Office. 2012.
[106] KULI Newsletter < engineering.mpt.magna.com/KULI-Newsletter-07-2016.5879.0.html?&cHash = ca874fd1a7a69702d8a7710b362ef6fc&tx_ttnews%5Btt_news%5D = 1837 > [accessed: 2018-02-27].
[107] Markus Wawzyniak, Marcus Weinbrenner, Achim Wiebelt, MAHLE. Battery Thermal Management Architectures and Components. SAE 2015 Thermal Management Systems Symposium 2015.
[108] I.L. Krüger, D. Limperich, G. Schmitz, Energy consumption of battery cooling in hybrid electric vehicles. 2012.
[109] P. Kritzer, H. Döring, B. Emermacher, Improved safety for automotive lithium batteries: an innovative approach to include an emergency cooling element, Adv. Chem. Eng. Sci. 4 (2014) 197.
[110] R. Baetens, B.P. Jelle, A. Gustavsen, Phase change materials for building applications: a state-of-the-art review, Energy Build. 42 (2010) 1361–1368.
[111] A. Elefsiniotis, T. Becker, U. Schmid, Thermoelectric energy harvesting using phase change materials (PCMs) in high temperature environments in aircraft, Electronic Materials 43 (2014) 1809–1814.
[112] F. Kuznik, D. David, K. Johannes, J.J. Roux, A review on phase change materials integrated in building walls, Renew. Sustain. Energy Rev. 15 (2011) 379–391.
[113] J. Jaguemont, N. Omar, P. Van den Bossche, J. Van Mierlo, Phase-change materials (PCM) for automotive applications: a review, Appl. Therm. Eng. 132 (2018) 308–320.
[114] S. Al Hallaj, J.R. Selman, A novel thermal management system for electric vehicle batteries using phase-change material, Electrochem. Soc. 147 (2000) 3231–3236.
[115] A. Sharma, V.V. Tyagi, C.R. Chen, D. Buddhi, Review on thermal energy storage with phase change materials and applications, Renew. Sustain. Energy Rev. 13 (2009) 318–345.
[116] R. Kizilel, R. Sabbah, J.R. Selman, S. Al-Hallaj, An alternative cooling system to enhance the safety of Li-ion battery packs, Power Sources 194 (2009) 1105–1112.
[117] C. Huber, Phase Change Material in Battery Thermal Management Applications. PhD Thesis. Technische Universität München, 2017.
[118] S. Wilke, B. Schweitzer, S. Khateeb, S. Al-Hallaj, Preventing thermal runaway propagation in lithium ion battery packs using a phase change composite material: An experimental study, Power Sources 340 (2017) 51–59.
[119] Z. Ling, F. Wang, X. Fang, X. Gao, Z. Zhang, A hybrid thermal management system for lithium ion batteries combining phase change materials with forced-air cooling, Appl. Energy 148 (2015) 403–409.
[120] Z. Wang, Z. Zhang, L. Jia, L. Yang, Paraffin and paraffin/aluminum foam composite phase change material heat storage experimental study based on thermal management of Li-ion battery, Appl. Therm. Eng. 78 (2015) 428–436.
[121] Y. Lv, X. Yang, X. Li, G. Zhang, Z. Wang, C. Yang, Experimental study on a novel battery thermal management technology based on low density polyethylene-enhanced composite phase change materials coupled with low fins, Appl. Energy 178 (2016) 376–382.
[122] W. Wu, W. Wu, S. Wang, Thermal optimization of composite PCM based large-format lithium-ion battery modules under extreme operating conditions, Energy Convers. Manage. 153 (2017) 22–33.
[123] J. Zhao, P. Lv, Z. Rao, Experimental study on the thermal management performance of phase change material coupled with heat pipe for cylindrical power battery pack, Exp. Therm Fluid Sci. 82 (2017) 182–188.
[124] C.V. Hémery, F. Pra, J.F. Robin, P. Marty, Experimental performances of a battery thermal management system using a phase change material, Power Sources 270 (2014) 349–358.
[125] X. Duan, G.F. Naterer, Heat transfer in phase change materials for thermal management of electric vehicle battery modules, Int. J. Heat Mass Transf. 53 (2010) 5176–5182.
[126] R. Kizilel, A. Lateef, R. Sabbah, M.M. Farid, J.R. Selman, S. Al-Hallaj, Passive control of temperature excursion and uniformity in high-energy Li-ion battery packs at high current and ambient temperature, Power Sources 183 (2008) 370–375.
[127] Z. Rao, Y. Huo, X. Liu, G. Zhang, Experimental investigation of battery thermal management system for electric vehicle based on paraffin/copper foam, Energy Institute 88 (2015) 241–246.
[128] W. Wu, X. Yang, G. Zhang, X. Ke, Z. Wang, W. Situ, X. Li, J. Zhang, An experimental study of thermal management system using copper mesh-enhanced composite phase change materials for power battery pack, Energy 113 (2016) 909–916.
[129] N. Javani, I. Dincer, G.F. Naterer, B.S. Yilbas, Heat transfer and thermal management with PCMs in a Li-ion battery cell for electric vehicles, Heat Mass Transf. 72 (2014) 690–703.
[130] N. Javani, I. Dincer, G.F. Naterer, G.L. Rohrauer, Modeling of passive thermal management for electric vehicle battery packs with PCM between cells, Appl. Therm. Eng. 73 (2014) 307–316.
[131] W. Wu, W. Wu, S. Wang, Thermal management optimization of a prismatic battery with shape-stabilized phase change material, Heat Mass Transf. 121 (2018) 967–977.
[132] Z. Rao, S. Wang, M. Wu, Z. Lin, F. Li, Experimental investigation on thermal management of electric vehicle battery with heat pipe, Energy Convers. Manage. 65 (2013) 92–97.
[133] M.S. Wu, K.H. Liu, Y.Y. Wang, C.C. Wan, Heat dissipation design for lithium-ion batteries, Power sources 109 (2002) 160–166.
[134] T.H. Tran, S. Harmand, B. Sahut, Experimental investigation on heat pipe cooling for Hybrid Electric Vehicle and Electric Vehicle lithium-ion battery, Power Sources 265 (2014) 262–272.
[135] Y. Ye, L.H. Saw, Y. Shi, A.A. Tay, Numerical analyses on optimizing a heat pipe thermal management system for lithium-ion batteries during fast charging, Appl. Therm. Eng. 86 (2015) 281–291.
[136] R. Zhao, J. Gu, J. Liu, An experimental study of heat pipe thermal management system with wet cooling method for lithium ion batteries, J. Power Sources 273 (2015) 1089–1097.
[137] F. Liu, F. Lan, J. Chen, Dynamic thermal characteristics of heat pipe via segmented thermal resistance model for electric vehicle battery cooling, Power Sources 321 (2016) 57–70.
[138] L. Feng, S. Zhou, Y. Li, Y. Wang, Q. Zhao, C. Luo, G. Wang, K. Yan, Experimental investigation of thermal and strain management for lithium-ion battery pack in heat pipe cooling, Energy Storage 16 (2018) 84–92.
[139] X. Ye, Y. Zhao, Z. Quan, Experimental study on heat dissipation for lithium-ion battery based on micro heat pipe array (MHPA), Appl. Therm. Eng. 130 (2018) 74–82.
[140] Z. Rao, Y. Huo, X. Liu, Experimental study of an OHP-cooled thermal management system for electric vehicle power battery, Exp. Therm Fluid Sci. 57 (2014) 20–26.
[141] Q. Wang, B. Jiang, Q.F. Xue, H.L. Sun, B. Li, H.M. Zou, Y.Y. Yan, Experimental investigation on EV battery cooling and heating by heat pipes, Appl. Therm. Eng. 88 (2015) 54–60.
[142] J. Liang, Y. Gan, Y. Li, Investigation on the thermal performance of a battery thermal management system using heat pipe under different ambient temperatures, Energy Convers. Manage. 155 (2018) 1–9.

[143] M.H. Elsheikh, D.A. Shnawah, M.F.M. Sabri, S.B.M. Said, M.H. Hassan, M.B.A. Bashir, M. Mohamad, A review on thermoelectric renewable energy: Principle parameters that affect their performance, Renew. Sustain. Energy Rev. 30 (2014) 337–355.
[144] W. He, G. Zhang, X. Zhang, J. Ji, G. Li, X. Zhao, Recent development and application of thermoelectric generator and cooler, Appl. Energy 143 (2015) 1–25.
[145] N. Espinosa, M. Lazard, L. Aixala, H. Scherrer, Modeling a thermoelectric generator applied to diesel automotive heat recovery, J. Electron. Mater. 39 (2010) 1446–1455.
[146] M.A. Karri, E.F. Thacher, B.T. Helenbrook, Exhaust energy conversion by thermoelectric generator: Two case studies, Energy Convers. Manage. 52 (2011) 1596–1611.
[147] L.N. Goenka, D.T. Crane, L.E. Bell, Thermoelectric based heating and cooling system for a hybrid-electric vehicle. U.S. Patent No 7,246,496, 2007.
[148] D. Zhao, G. Tan, A review of thermoelectric cooling: materials, modeling and applications, Appl. Therm. Eng. 66 (2014) 15–24.
[149] C. Alaoui, Z.M. Salameh, A novel thermal management for electric and hybrid vehicles, IEEE Trans. Veh. Technol. 54 (2005) 468–476.
[150] X. Zhang, KT C, CC C. Overview of thermoelectric generation for hybrid vehicles. Asian Electric Vehicles 2008;6:1119-24.
[151] L.T. Yeh, R.C. Chu, Thermoelectric Coolers. ASME Press, 2002.
[152] L.E. Bell, Cooling, heating, generating power, and recovering waste heat with thermoelectric systems, Science 321 (2008) 1457–1461.
[153] C. Alaoui, Solid-state thermal management for lithium-ion EV batteries, IEEE Trans. Veh. Technol. 62 (2013) 98–107.
[154] V. Esfahanian, S.A. Renani, H. Nehzati, N. Mirkhani, M. Esfahanian, O. Yaghoobi, A. Safaei, Design and Simulation of Air Cooled Battery Thermal Management System Using Thermoelectric for a Hybrid Electric Bus, Springer, Berlin, Heidelberg, 2013, pp. 463–473.
[155] Y. Liu, S. Yang, B. Guo, C. Deng, Numerical analysis and design of thermal management system for lithium ion battery pack using thermoelectric coolers, Adv. Mech. Eng. 6 (2014) 852712.
[156] Y. Troxler, B. Wu, M. Marinescu, V. Yufit, Y. Patel, A.J. Marquis, N.P. Brandon, G.J. Offer, The effect of thermal gradients on the performance of lithium-ion batteries, J. Power Sources 247 (2014) 1018–1025.
[157] M. Broussely, Battery requirements for HEVs, PHEVs, and EVs: an overview. Electric and Hybrid Vehicles: Power Sources, Models, Sustain., Infrastructure Market (2010) 305–347.
[158] Kim KS. Automotive, Next-generation Battery Technology applications (presentation). Hanon System Seminar in Korea Electronics, Technology Institute (KETI) (2017).
[159] W. Wu, X. Yang, G. Zhang, K. Chen, S. Wang, Experimental investigation on the thermal performance of heat pipe-assisted phase change material based battery thermal management system, Energy Convers. Manage. 138 (2017) 486–492.
[160] T. Yamada, T. Koshiyama, M. Yoshikawa, T. Yamada, N. Ono, Analysis of a lithium-ion battery cooling system for electric vehicles using a phase-change material and heat pipes, Thermal Science Technol. (2017) 12.1.
[161] Q. Wang, Z. Rao, Y. Huo, S. Wang, Thermal performance of phase change material/oscillating heat pipe-based battery thermal management system, Thermal Sciences 102 (2016) 9–16.
[162] Z. Rao, Q. Wang, C. Huang, Investigation of the thermal performance of phase change material/mini-channel coupled battery thermal management system, Appl. Energy 164 (2016) 659–669.
[163] Y. Wei, M. Agelin-Chaab, Experimental investigation of a novel hybrid cooling method for lithium-ion batteries, Appl. Therm. Eng. 136 (2018) 375–387.
[164] H.S. Lee, J.W. Kim, Battery cooling unit and battery module including the same. KR. Patent No. 10-2018-0029056. 2018.