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Review

A critical review of battery thermal performance and liquid based battery thermal management

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ABSTRACT

Electric vehicles with green power system are viable alternatives to reduce greenhouse gas emissions and dependence on fossil energy resources. The power source such as Li-ion battery has high sensitivity to temperature, which is a challenge related to battery thermal management. Battery thermal management system plays a vital role in the high efficiency, dependability and security of these batteries. Modern commercial electric vehicles normally use liquid based battery thermal management system, which has high heat transfer efficiency with the function of cooling or heating. This paper firstly looks at the effects of temperature on the battery performance from three aspects: low temperature, high temperature and differential temperature. Then the battery management system is discussed with the main emphasis on battery modeling methods and thermal management strategies. Further, a systematic review of liquid based system is presented in terms of direct and indirect contact mode. Progress made in liquid channel configuration and heat transfer fluid aiming at improving the overall thermal performance is also discussed. With the function of liquid-gas phase change process, the heat pipe based battery thermal management is feasible and effective for its high heat transfer efficiency. To further facilitate vehicle-mounted energy optimization, an integrated vehicle thermal management system with appropriate energy allocation is required. In addition, the battery thermal management system connected with the other subsystems (e.g., heating ventilation air conditioning system) by utilizing the liquid circulation in vehicle thermal management has great potential in energy-saving and efficiency promotion.

1. Introduction

The global issues of energy shortage and environmental pollution have made the growing popularity of electric vehicles (EVs) and hybrid electric vehicles (HEVs) to take center stage in the future [1]. EVs and HEVs are generally regarded as sustainable solutions to replace the traditional internal combustion engine technology with electric motors. The primary power source for these electric motors is the power battery system. Nowadays, different kinds of batteries such as NiCd, NiMH and Li-ion battery have been proposed and used for EVs and HEVs. Among all these types of batteries available for major EV productions such as GM, Honda, Toyota, Ford, Mitsubishi, Renault and Peugeot in the market, NiCd and NiMH were the most popular two date back to 2000 [2]. However, in recent years, Li-ion battery has been widely employed in EVs manufacturers because of its significant advantages such as relatively low self-discharge rate, long cycle life, high power and energy density [3].

Batteries used in automotive applications can be divided into three grades: cell, module and pack. In order to get enough power and energy, battery cells are always connected in different configurations to constitute a module or even a pack. For these demanding applications, the batteries are considered sensitive to pressure, vibration and temperature. Among them, storage or operating temperature will affect the battery performance, and the temperature maldistribution in the module/pack can cause different electrochemical behaviors and electrically unbalanced cells. Generally, low temperature can depress the power and energy of batteries heavily [4]. In addition, the batteries may also encounter a problem known as capacity fading because of the non-uniformity of solid electrolyte interface (SEI) layer and electrolyte decomposition at high temperature [5]. Moreover, batteries are vulnerable to serious issues such as short circuit and excessive ambient temperature, which can cause overheating and failure of batteries. Hence, developing an effective cooling and heating system to control the battery temperature within a specified range is an important task for EVs and HEVs.

Nowadays, considerable research efforts have been devoted to

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developing an advanced battery thermal management (BTM) system which can be categorized as several types such as: active or passive [6], series or parallel [7], heating or cooling [8], internal or external [9], air or liquid or phase change material (PCM) [10], or hybrid strategy combining multiple methods. Different types have their own advantages and disadvantages. The choice of a suitable BTM system depends on many factors such as volumetric constraints, installation costs and working efficiency. The BTM strategies now available are always investigated to close the key technological gaps between commercial manufacturers and researchers. Modern EVs and HEVs normally use active methods and leading commercial vehicles (e.g., Chevrolet Volt, Tesla Model S and Model 3, BMW i3 and i8) use liquid based system [11]. This system has high heat transfer efficiency with the function of cooling or heating, which make it a more suitable strategy for BTM. In this paper, the influence of temperature on the battery performance is documented firstly. Then the battery management system is discussed with the main emphasis on modeling methods, external and internal thermal management strategies. In what follow, a systematic review of liquid based BTM system is presented. Conclusions are made in the last section and offer some suggestions for future development of BTM system.

2. Overview of previous reviews

In order to take a detailed look at the content of this paper, it is essential to survey the outlines of earlier reviews published in the fields of BTM strategies. Table 1 lists the review papers about different BTM technologies with thermal behavior, modeling methods and operating conditions. Various technologies incorporated in BTM system were reviewed by many researchers, but most of their works were limited to detailed insights into liquid based system. This is the main object of this review.

3. Effect of temperature on battery performance

In the actual applications, batteries are required to work at different temperature levels. The goal of this chapter is to document the influence of temperature on batteries from three aspects: low temperature performance, high temperature performance and differential temperature performance.

3.1. Low temperature

At low temperature, the battery performance is clearly reduced, which will limit their use in cold climates and high-altitude drones such as Canada and Russia [23]. Generally, it is thought that low temperature can affect batteries in several ways including charge acceptance [24], energy and power capacity [25], round-trip efficiency and lifespan [26]. Smart et al. [27] charged Li-ion cell at low temperature and found that it was hard to charge the cell to its capacity as obtained at room temperature and lithium plating might occur at high charging rates. It was reported that both power and energy of Li-ion batteries could be reduced once the temperature fell down to $-10\,^{\circ}C$ [4]. With a lower temperature of $-40\,^{\circ}C$, the power and energy density could be delivered only 1.25% and 5%, respectively, as compared with the values obtained at $20\,^{\circ}C$ [25]. Besides poor performance, the aging rate of LIBs will be accelerated during cycling conditions at low temperature especially below $0\,^{\circ}C$. At a low temperature of $-10\,^{\circ}C$, Ouyang et al. [28] found that an 11.5 Ah Li-ion cell had a capacity loss of 25% after only being cycled 40 times at a charge rate of 0.5 C. The capacity decrease mainly occurred in the initial stage of cycling conditions and lithium plating was generally considered to be the major degradation mechanism [24]. Previous studies have been devoted to study the low temperature cycling performance and deduced degradation mechanisms with various factors such as temperature [29], charging rate [28], discharging rate [30], cell chemistry and format [31].

According to the previous studies, the mechanism of the poor performance at low temperatures may can be summarized in four respects:

Table 1
Review papers relevant to BTM technology.

Reference	Subject	Remarks
Cosley and Garcia [12] in 2004	Split cooling system for valve-regulated lead acid batteries	Trade off analysis for different battery cooling solutions like buried vault, fan forced convection, PCM, thermosyphon, thermoelectric, air conditioner and cold plate
Bandhauer et al. [13] in 2011	Thermal issues for Li-ion batteries	A detailed summary about the impact of temperature on capacity/power fade, electrical imbalance and thermal runaway. low temperature performance, thermal modeling and thermal management strategies were also elucidated
Rao and Wang [10] in 2011	Battery thermal energy management	Three types of conventional air-based, liquid-based and PCM-based BTM systems with focus on the thermal conductivity enhancement of PCM
Xu and He [14] in 2014	Heat dissipation performance	Thermal performance of battery pack with different structures and operating conditions
Ling et al. [15] in 2014	PCM use in thermal management system	A review of thermal management systems using PCM for electronic devices, photovoltaic modules and batteries with focus on the thermal properties of PCM
Zhao et al. [16] in 2015	Thermal performance improving methods for Li-ion batteries	Thermal behavior, interior electrode modifications and exterior thermal management systems were gathered
Shabani and Biju [17] in 2015	Theoretical modelling methods for batteries	Different methods for modeling the thermal behavior and thermal management systems of batteries
Saw et al. [7] in 2015	Integration issues of Li-ion batteries	Battery chemistry, cell packaging, electric connection, assembly, maintenance, and thermal management were investigated from the integration point of view
Effat et al. [9] in 2016	Thermal management and safety of Li-ion batteries	Electrochemical and electrochemical-thermal models of Li-ion batteries; suitable cooling technologies and thermal runway modeling
Jaguemont et al. [18] in 2016	Li-ion batteries at cold temperatures	Capacity/power fade and aging mechanisms at cold temperatures; extensive attention on thermal management strategies along with a discussion of heating strategies
Wang et al. [2] in 2016	Thermal management models and solutions for Li-ion batteries	Li-ion batteries for EVs and HEVs, and the development of battery thermal model and thermal management strategies
Malik et al. [19] in 2016	PCM use in BTM system	Challenges and opportunities for battery electric vehicles; heat transfer enhancement techniques for PCM based BTM systems
Pan et al. [20] in 2016	PCM use in BTM system	Heat transfer enhancement methods for PCM; configuration, hybrid method, heating and cooling for PCM based system
An et al. [21] in 2017	Thermal management and safety of Li-ion batteries	Heat generation characteristic, thermal safety and extensive attention on thermal management strategies
Liu et al. [22] in 2017	Thermal issues and Thermal management of Li-ion batteries	Battery performance, battery modeling and thermal management strategies

(1) low ionic conductivity of electrolyte solution [32]; (2) limited solid-state diffusivity of Li-ion [33]; (3) high polarization in the carbon anode [34]; and (4) high charge-transfer resistance on the electrolyte-electrode interfaces [35]. In addition, the acknowledged degradation mechanisms can be grouped into three modes: the increase of resistance, loss of active materials (LAM) and loss of lithium inventory (LLI). In an effort to improve the performance at low temperature, researches were focused primarily on developing new types of materials including cathode, anode, solvent and lithium salt for electrolytes [36,37,38,39]. The electrolytes with high ionic conductivities and low freezing points [40,41] were mostly developed by blending several solvents to ternary and quaternary electrolytes [42] or using functional electrolyte additives [43].

3.2. High temperature

At high temperature, there are several adverse effects exert on battery performance such as capacity/power fade and self-discharge [13], and these effects can even make the available energy suffer huge loss [44,45]. Bandhauer et al. [13] have documented the capacity and power fade of various positive electrode materials under high temperature cycling and storage, it showed that the capacity appeared to degrade when the temperature increased above ∼50 °C. For instance, the Sony 18650 cells had a capacity loss of 36% after being cycled 800 times at 45 °C and lost more than 70% at 55 °C after 490 cycles [46]. Thomas et al. [47] conducted an accelerated aging experiment to study the impact of aging time and temperature on the performance of Li-ion cells, which showed that a power fade of 55% was obtained over the storage course of 20 weeks at 55 °C. The capacity/power fade of battery has been studied in detail in Ref. [48], and the possible reasons of capacity fade were LAM and LLI [49]. In this stage, active material could be transformed to inactive phases leading to the loss of available energy. However, the available energy loss caused by active material decline was just a small piece of the total capacity loss at low temperature, while it predominated at higher temperature [50]. In addition, batteries could inevitably self-discharge after storing at a variety of temperatures, and the increased electronic conductivity caused by the dissolution of surface species could increase the rate of self-discharge [13]. Besides exposed to high temperature for an extended period, the self-discharge of batteries could be abnormally accelerated even to a routine short-time exposure because of the memorized thermal "history" [51].

Safety is a priority and serious issue for EVs. Besides the poor performance at high temperature, each cell in the battery module is vulnerable to overheating from short circuit and excessive ambient temperature. When the process of self-heating is out of control, thermal runway (TR) may occur with the advent of fire and explosion. For Li-ion cells, a general path to TR can be divided into three stages [52,53]: (1) initial TR regime; (2) cell venting and runway; (3) explosive decomposition reaction. What is more, Lu et al. [54] illustrated a more detailed path that progressed to TR according to the triggered temperatures of different heat producing exothermic reactions [13]. The detail mechanism of chain reactions during TR was performed by Feng et al. [55]. Table 2 summarizes the exothermic reactions of Li-ion cells varying with temperature. It shows that the SEI layer will start exothermic decomposition when the temperature is 90–130 °C or at a lower temperature of about 69 °C [56], and once the layer is breached, the negative electrode will react with organic electrolyte and then combustion gas is produced [57]. At around 130 °C, the separator will start melting and allowing the short circuits between the electrodes [58]. With the temperature increasing, the commonly used positive electrode material will start decomposing and producing oxygen. The released oxygen and heat over the reaction process provide the required conditions for fire and explosion for batteries.

Table 2
Exothermic reactions and thermal stability of Li-ion batteries (modified from [2,54,58]).

Temperature(°C)	Associated reaction	Comment
		Fire and explosion
Above 310	Positive material decomposition	$LiFePO_4$ breakdown and releases oxygen
Above 265	Positive material decomposition	$LiMn_2O_4$ oxidated and releases oxygen
240-250	LiC_6+binder	
240-250	LiC_6+electrolyte	
200-230	Positive material decomposition	O_2 emission reacts with solvents; above 210°C, $LiCo_xNi_yMn_zO_2$ breakdown and releases oxygen
Above 200	Electrolyte decomposition	The electrolyte decomposes and reacts with the electrodes, releases flammable gases
200	Solvents-$LiPF_6$	Slow kinetic
160-170	PP separator melts	Endothermic
Above 160	Positive material decomposition	$LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ breakdown and releases oxygen
Above 150	Positive material decomposition	$LiCoO_2$ breakdown and releases oxygen
130-140	PE separator melts	Endothermic
90-130	SEI decomposition	SEI begins to decompose, release heat; solubilisation starts below 100 ° C, release flammable hydrocarbon gases (ethane, methane and others) but no oxygen

3.3. Differential temperature

Besides the low and high temperature performance, a uniform temperature distribution is another key to ensure batteries work efficiently. Good temperature uniformity needs to be evaluated from cell, module and pack levels. Temperature maldistribution in the cell, module or pack could cause different charging or discharging behaviors and electrochemical performance. As the geometric characterization and thermal physical properties of components inside the cell are different, the heat generation in different components and the heat transfer in all directions are significantly different, thus temperature gradient within the cell will be developed [59]. Based on the Arrhenius law, the electrochemical reaction rate will increase exponentially as the temperature increases [60]. As indicated by Rao [61], the temperature near the electrode was higher than in other places of the cell. Such uneven temperature distribution will lead to non-uniform electrode reaction rates [2] and then reduce the cell performance and cycle life [7].

Normally one module is constituted by a number of cells, but there are inevitably some differences between each cell such as capacity, voltage and internal resistance [54]. These mismatches will lead to different charging or discharging behaviors, giving rise to an uneven temperature distribution in the module [62]. The cells with different working temperatures have different aging processes, resulting in lower capacity utilization for module [54]. Feng et al. [63] proposed a method to investigate the status change of cell variations caused by temperature non-uniformity in the battery pack and the results showed that 5 °C increase in temperature difference could cause 1.5–2% capacity loss of the pack. In another study, Kuper et al. [64] discussed the efficient thermal control strategies in a demanding automotive environment, it showed that a temperature difference of just 5 °C could lead to the degradation of about 10% of the power capability. In order to achieve better performance, the temperature distribution from cell to cell as well as module to module should not exceed 5 °C was suggested. Furthermore, short circuits or internal defects within individual cell and heat dissipation condition at the center and edge of module may result in 'hotspots' within the module/pack, leading to thermal runaway and catastrophic failure [65]. A detailed investigation into the fire that occurred in a modified Toyota Prius vehicle was reported in Ref. [66], it demonstrated that improper assembly will cause excessive heating and then lead to the rupture of individual battery cells. Such a scenario could escalate to severe failures at module/pack level and ultimately vehicle fire if no appropriate means were adopted to prevent the propagation of TR. The Fire damaged vehicle and empty battery cells can be seen in Fig. 1.

4. Battery system

Generally, a battery system is made up of a number of individual cells to fulfill the requirement of voltage and power. Besides the cells, the battery system contains other components such as cell housings, electronic controls, sensors, bus bars and ducting, which can lead to a relatively complex configuration [67]. Although the research of battery technology with higher power and energy density has got some achievement, the progress in materials and cell design alone cannot ensure a solution that will overcome all the concerns [68]. To manage

Fig. 1. Fire damaged vehicle and battery cells [66].

so many cells and obtain maximum performance under various operating conditions, it makes sense to have an efficient battery management system (BMS). In addition, the BMS allows helping the battery system to preserve the thermal limits of the cells and improve the energy management.

4.1. Battery management system

A BMS is essentially the "brain" of a battery module/pack, which features the ability to monitor and balance the individual cells in spite of the definition of BMS is still no consensus. BMS consists of kinds of devices such as sensor, actuator, and controller which has various algorithms and signal wires [54]. Fig. 2 shows a common BMS framework with the basic functions including cell parameters detection, estimation of cell status, on-line diagnosis, cell protection and equalization, thermal management control and communication [54]. The BMS is very important from functional point of view as it can protect the cells from working outside the safety area such as over-current, over/under-voltage and over/under-temperature [69]. The data acquisition captures individual cell voltage, current, and temperature by various sensors at the battery monitoring layer. All of these real-time collected data are then used to estimate the battery status in later stage. Among these status, the state-of-charge (SOC) and state-of-health (SOH) are of particular interest since they are the equivalents of available capacity and useful lifetime for the battery pack [70]. The battery states determine the outputs such as the charge/discharge strategy and the thermal management with cooling/heating control. To achieve the best performance, the battery cells should all have nearly the same electrical characteristics, which are strictly dependent on the temperature. A shared galvanic-isolated controller area network (CAN) bus is usually performed as a standard communication protocol to implement communication among these units [68].

4.2. Battery thermal management strategies

A typical BTM is a responsive system that use different heating/cooling methods to keep the temperature of battery pack within a desirable range under the control of an electronic control unit in BMS (as shown in Fig. 2). Due to the significant effects of temperature on batteries as discussed in Section 3, considerable studies and efforts have been invested to develop an advanced BTM system which is summarized as external and internal types in this section.

4.2.1. Model and simulation

There are many methods to investigate and optimize the design of battery cells and BTM strategies, in which modeling and simulation are the most popular. Models can provide insights into the physical mechanism of battery behaviors (e.g., electric, electrochemical and thermal) to predict battery performance in controlled conditions [73]. Battery modeling involves two categories of electrochemical model and

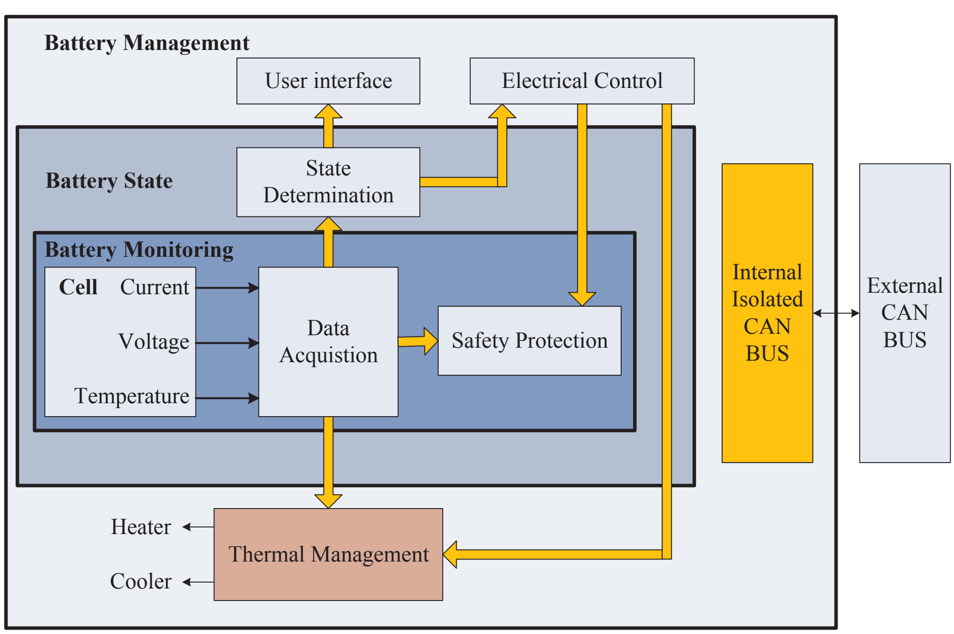


Fig. 2. Illustration of a BMS.
Adapted from [68,71,72].

electrical equivalent circuit model according to the different modeling approaches [74]. The electrochemical model provides complete information on the electrochemical actions and reactions of a cell with a set of partial differential equations, and the widely employed electrochemical model can be seen in the pioneering work performed by Newman and coworkers [75,76]. Several review papers about the main electrochemical models can be seen elsewhere [73,77,78,79]. Generally, the electrochemical model can be the single particle model (SP model), porous electrode model with the polynomial approximation (PP model) and pseudo two-dimensional model (P2D model) in order of increasing complexity. Although the electrochemical model is accurate, this model is complex and needs very powerful computing resources to solve the non-linear differential equations, which is not directly applicable to intended application in power and dynamic systems studies. Instead, many modeling efforts have been focused on simplification (e.g., order-reduction model) to get faster simulation [80,81,82].

Electrical equivalent circuit model is another useful model that neglects the complex electrochemistry of the cell and puts common electronic components such as capacitors and resistors in a circuit. The simplest form is the internal resistance model consisting of a resistance (R_o) and an ideal voltage sources (V_{oc}), with terminal equation described by Eq. (1) [83]. Further increase in accuracy and fidelity can be acquired by adding more electronic components to this model. Typical equivalent circuit models for battery are summarized in Table 3 and an overview of the applications of each model can be seen in Ref. [74]

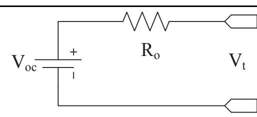
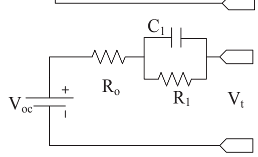
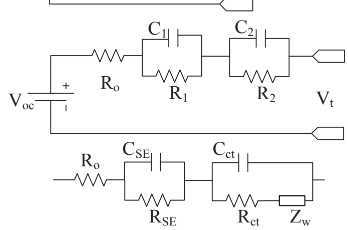
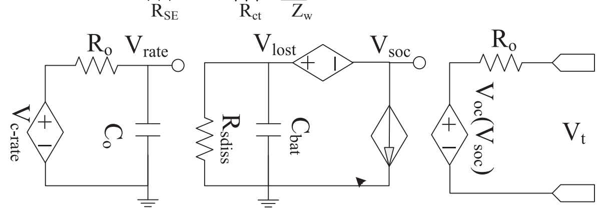
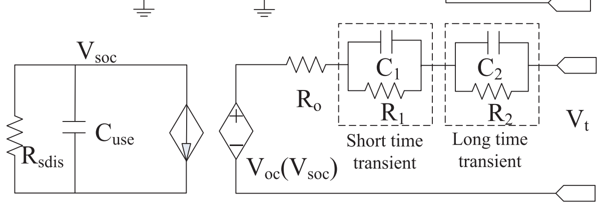
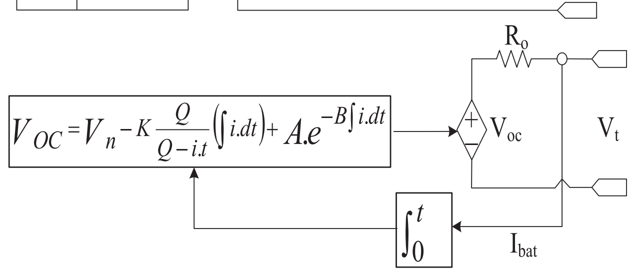
$$V(t) = V_{oc} - R_o I(t) \tag{1}$$

In addition, battery thermal model that can simulate thermal performance and improve the design process of BTM has been developed in many studies. This model is primarily based on the energy conservation equation as follow:

$$mC_p \frac{dT}{dt} = Q_{gen} - Q_{dis} \tag{2}$$

where m is the cell mass, C_p is the heat capacity, T is the cell temperature and the left side of the equation is the heat stored by the cell; Q_{gen} is the generated heat during battery operation, and Q_{dis} is the dissipated heat due to conduction, convection or radiation. As the chemical reactions in the cells are very complex, the heat generation is difficult to determine which depends on the chemistry type, charge/discharge profile, construction, ambient temperature and SOC. As illustrated in Fig. 3, the total heat generation is comprised of reversible and irreversible terms. A thermal model based on thermodynamic energy balance was firstly proposed by Bernardi et al. [84] and the heat

Table 3
Electrical equivalent circuit model.
Adopted from [74].

Simple model		V_{oc}	Ideal open-circuit voltage
		R_o	Internal series resistance
		V_t	Terminal voltage
Thevenin-based model		C_1	Capacitor
		R_1	Overvoltage resistance
Impedance-based model		R_{SE}	Resistance of the surface film layer
		C_{SE}	Capacitance of the surface film layer
		R_{ct}	Charge transfer resistance
		C_{ct}	Double layer capacitance between the electrode and electrolyte
		Z_w	Warburg impedance
Runtime-based model		R_o	Charge storage resistor
		C_o	Charge storage capacitor
		C_{bat}	Battery capacitor
		R_{sdiss}	Self-discharge resistor
Combined electrical circuit-based model		C_{use}	Capacity of the battery
		R_o	Ohmic resistance
		R_1	Short time constants
		R_2	Long time constants
Generic-based model		Q	Capacity of the battery
		K	Polarization resistance
		V_n	Battery constant voltage
		A	Exponential zone amplitude (V)
		B	Exponential zone time constant inverse $(Ah)^{-1}$
		$\int i.\,dt$	Actual battery charge (Ah)

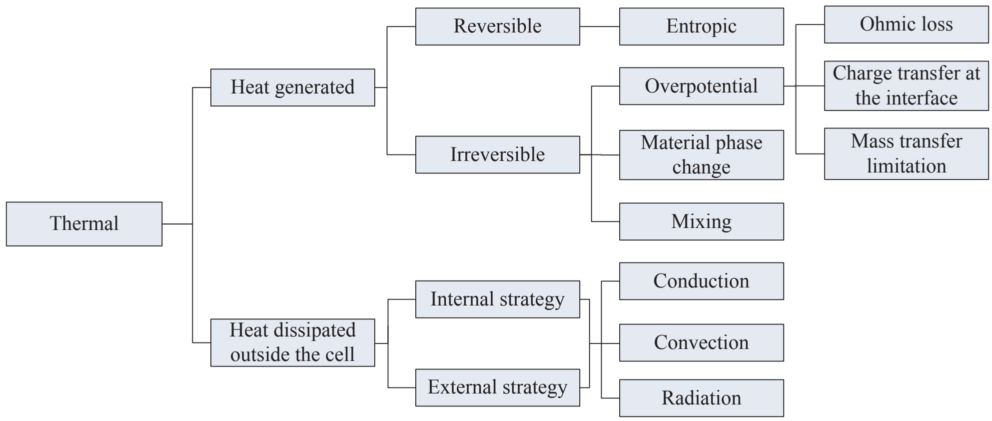


Fig. 3. Battery thermal issues [73].

generation could be expressed as follow:

$$Q_{gen} = -IV - \sum_{l} I_l T^2 \frac{d\frac{U_{l,avg}}{T}}{dT} + \sum_{j} \frac{d}{dt}\left[\int_{v_j} \sum_{i} c_{i,j} RT^2 \frac{\partial}{\partial T} \ln\left(\frac{\gamma_{i,j}}{\gamma_{i,j}^{avg}}\right) dv_j\right] + \sum_{j,j\neq m} \sum_{i}\left[\left(\Delta H_{i,j\to m}^{o} - RT^2 \frac{d}{dT} \ln \frac{\gamma_{i,m}^{avg}}{\gamma_{i,j}^{avg}}\right) \frac{dn_{i,j}}{dt}\right] \tag{3}$$

Here, the first term on the right side of this equation is the electrical power, the second term is the enthalpy of reaction, the third and final terms are the heat produced from mixing and material phase change, respectively. This equation may be more accurate but relatively complex. Therefore, a simplified form that neglects the mixing and phase change effects is cited frequently in the literatures:

$$Q_{gen} = I(U - V) - IT\left(\frac{\partial U}{\partial T}\right) \tag{4}$$

where U and V represent the open-circuit voltage and operating voltage, respectively. $I(U - V)$ and $IT\left(\frac{\partial U}{\partial T}\right)$ are the heat generation due to joule heating and entropy change, respectively. In addition to modeling studies, there are several techniques to experimentally measure the heat generation rate such as accelerated-rate calorimetry (ARC) [85], radiation calorimetry (RC) [86] and isothermal heat conduction calorimetry (IHC) [87].

To achieve a comprehensive analysis, thermal models must take into account the thermal properties and geometrical parameters of different components, and the boundary conditions of heat transfer. Several approaches have been used for battery thermal analysis, such as finite element method (FEM) [88], finite difference method (FDM) [89] and finite volume method (FVM) [90]. A thermal model can be thermally coupled or decoupled with electrochemical/electrical forms that simulates the battery thermal performance with various geometries such as 1-D, 2-D, or 3-D [91]. By assuming the battery temperature is spatially uniform during the heat transfer process, a lumped-parameter model (1-D) can be constructed. The applicability of this approximation method depends upon the number of the Biot number (*Bi*) which is the ratio of the internal heat transfer resistance to the surface heat exchange resistance of the battery. Generally, the lumped-parameter model is considered acceptable when *Bi* is less than 0.1. Some research works have used a simplified 1-D model with lumped parameters to simulate the thermal behaviors under different conditions [92,93]. By way of 2-D modeling, Karimi et al. [94] investigated the thermal management of thin-film flat type batteries according to the thermodynamic formulation performed by Inui et al. [95], where they simulated 2-D and 3-D temperature distributions in cylindrical and prismatic batteries. A 3-D thermal model coupled with electrochemical reactions can provide detail insights into the temperature field distribution and evaluation within cells [96]. Thus, 3-D thermal model can be used to analyze and optimize the thermal performance of BTM with different configurations [59].

4.2.2. External management

Based on the employment of different heat transfer mediums, external BTM system can be summarized as air, liquid or PCM based system. Desirable features of an external BTM system include compactness, low maintenance, low cost, vehicle compatibility and reliability [6]. And each of these systems has advantages and disadvantages that should be balanced with the actual requirements.

Air- In general, air-based system can be categorized into natural convection and forced convection. The main advantages of such a method are its simplicity and electrical safety over the other systems. It is apparent that the natural method has limitations in more demanding ambient conditions, and large thermal gradient among the pack can be occurred. Therefore, a forced air system is required and is mostly studied for its effectiveness to reduce the maximum temperature in spite of additional power requirements. The forced air source can be supplied from two ways: one is from the air-conditioned vehicle cabin (such as 2001 Toyota Prius), and the other is from ambient through a separate micro air conditioning unit. However, the heat capacity and thermal conductivity of air is much lower than many other mediums, thus air-based system still encounters the problems of temperature rise and temperature maldistribution among cells. Nelson et al. [97] argued that air based system was difficult to cool the batteries to less than 52 °C when the battery temperature was above 66 °C. Improvements towards air-based system have been widely studied in recent years with concentration on the optimization of the cell arrangement, air flow rate and flow path, and the other new technologies, which can be seen in Table 4.

Liquid- A liquid based system is more effective in cooling and less pumping power consumption than air based system due to its higher heat transfer coefficient [101]. In addition, liquid heating has been used in commercial vehicles such as the Chevrolet Volt, where the liquid is heated by electronic heaters. The detailed review of liquid based system can be seen in the next chapter, and considering the working fluid in heat pipe (HP) is used to complete liquid-gas phase transition, it is thought that HP is one of the liquid based strategies [10].

PCM- As an innovative solution for thermal management applications, PCM can absorb a lot of latent heat during its melting process, while the temperature is maintained around the phase change temperature for a long time (Fig. 4). Because of the unique property, PCM based BTM system has received extensive attention and exploration in recent years. PCM based system has potential to bring benefits, such as passively buffering against high operating temperature [120,121], extending life cycle and eliminating TR [122]. Paraffin is currently the preferred PCM for its low cost, high latent heat and suitable phase-change temperature. Lower maximum temperature and better

Table 4
Improvement methods for forced air based BTM system.

Reference	Battery type	Improvement	Variables or remarks
Fan et al. [98]	Prismatic	Air flow rate/Cell arrangement	Effects of fan's flow rate and space between neighboring cells
He et al. [99]	Cylindrical	Air flow rate/Cell arrangement	Various flow velocities, module configuration with different wall-cell distance
Yu et al. [100]	Prismatic	Air flow rate/Flow path	Effect of air flow rate and two-directional air flow
Park and Jung [101]	Cylindrical	Cell arrangement	A wide battery module with small gap is beneficial for temperature variation
Xun et al. [102]	Prismatic/Cylindrical	Cell arrangement	Effect of cooling channel number and size
Liu et al. [103]	Cylindrical	Cell arrangement/Flow path	Battery unit spacing and effects of the plate angle of the plenums
Wang et al. [104]	Cylindrical	Cell arrangement/Flow path	Rectangular, hexagonal and circular arrangement; fans at the different locations
Cho et al. [105]	Prismatic	Cell arrangement	Effects of the module arrangement
Reyes-Marambio [106]	Cylindrical	Cell arrangement	Staggered and aligned arrays
Mahamud and Park [107]	Cylindrical	Flow path	Reciprocating air flow to improve temperature uniformity
Park [108]	Prismatic	Flow path	Tapered manifold and pressure relief ventilation for air flow distribution
Yang et al. [109]	Cylindrical	Flow path	Aligned and staggered cell arrangement
He et al. [110 111]	Cylindrical	Flow path	Combine hysteresis [110] or reduced-order model based active control [111] with reciprocating cooling flow
Tong et al. [112]	Cylindrical	Air flow rate/Cell arrangement/ Flow path	Effects of staggered cell arrangement, air inlet velocity and periodic reversal air flow
Ismailov et al.[113]	Cylindrical	Flow path	Splitter plates and flow guide-vanes for cooling
Giuliano et al. [114]	Prismatic	–	Heat exchanger plates with metal foam
Mohammadian et al. [115]	Prismatic	–	Flow channels with metal foam
Mohammadian and Zhang [116]	Prismatic	–	Aluminum pin fin heat sink
Chen et al. [117]	Prismatic	Flow path	The angles of the plenums and the widths of the inlet and the outlet are optimized using the nested looped procedure
Chen et al. [118]	Prismatic	Cell arrangement	Battery spacing optimization with flow resistance network model
Chen et al. [119]	Prismatic	Flow path	The flow pattern and the inlet and outlet positions are optimized

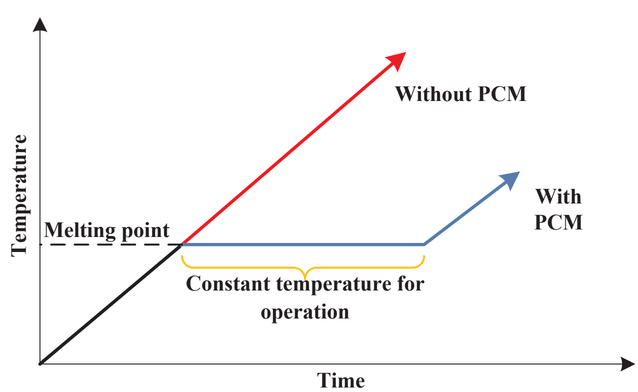


Fig. 4. Temperature characteristic of PCM based system.

temperature uniformity can be achieved for PCM compared to conventional systems, especially for large-scale batteries under high-rate discharge [122]. Nevertheless, significant challenges still remain in this technology: (1) weak structural strength and leakage of melted PCM; (2) relatively low thermal conductivity; (3) low surface heat transfer coefficient and run out of the available latent heat.

To reduce the liquid PCM leakage danger, containers are necessary and shape-stabilized PCM which consists of PCM as dispersed material and other materials as supporting material has attracted the interests of researchers [123,124]. With expanded graphite (EG) impregnated in the PCM, there will be no leakage during the phase change process because of the high porosity and absorbability of EG. The thermo-mechanical properties such as tensile strength, burst strength and compression strength of PCM/EG composites were investigated in Ref. [125]. To address the issues of leakage and strong rigidity, a novel form stable and thermally induced flexible composite PCM with olefin block copolymer as the supporting material was prepared by Wu et al. [126]. The good flexibility achieved by triggering the phase transition of paraffin could lead to many deformation modes such as bend and compression, which were beneficial for thermal contact resistance decrease and installation improvement. With respect to the enhanced thermal conductivity of PCM for BTM system, a second component made of high conductive materials such as metallic particle [127], metal foam [128], carbon fiber [129], graphene [130] and carbon nanotubes [131] has been widely introduced and studied. As the battery heats up, the high thermal additive acts as a thermal conductor or conductive network and distributes the heat evenly throughout the module/pack, avoiding hotspots and ensuring thermal uniformity.

Although PCM based system can control the battery temperature in normal conditions, accumulated heat should be dissipated in the long run or harsh working cycle conditions when the PCM is completely melted [59]. In addition, composite PCM generally presents low surface heat transfer capability, leading to a reducing of the effectiveness of heat dissipation [123]. Thus, a combined BTM system that integrated PCM with air forced convection [132,133] or fins [134,135] was conducted to improve the heat transfer capability and the overall thermal performance. Wu et al. [136] proposed a copper mesh-enhanced PCM/EG composite based BTM system, in which the copper mesh could increase the strength and thermal conductivity of shape-stabilized PCM (Fig. 5(a)). The fins exposed from the composites could play an important role in disturbing the air flow and thus further enhance the heat dissipation capacity, and the results showed that this system presented much better thermal performance compared to PCM/EG without copper mesh. Another improvement method is that the PCM coupled with HP (Fig. 5(b)) [137] or liquid channel (Fig. 5(c)) [138], which has the excellent cooling effect to remove heat from modules to exterior environment.

4.2.3. Internal management

On account of the undesirable temperature increase and thermal gradient caused by external thermal management removing heat from the exterior surface, internal thermal management has also been developed and is receiving growing attention. Internal thermal management is normally applied in the batteries at cell level, and the cooling and heating strategies exist in the core region of the battery monomer.

In 1979, Choi and Yao [139] proposed a cooling method to remove the heat generated within the lead-acid cell by means of electrolyte circulation. It showed that such an approach could be quite effective in providing a uniform temperature field and the temperature could be maintained at a desirable level by controlling the rate of electrolyte circulation. Similarly, Mohammadian et al. [140] introduced a particular type of internal cooling method, where liquid electrolyte served as

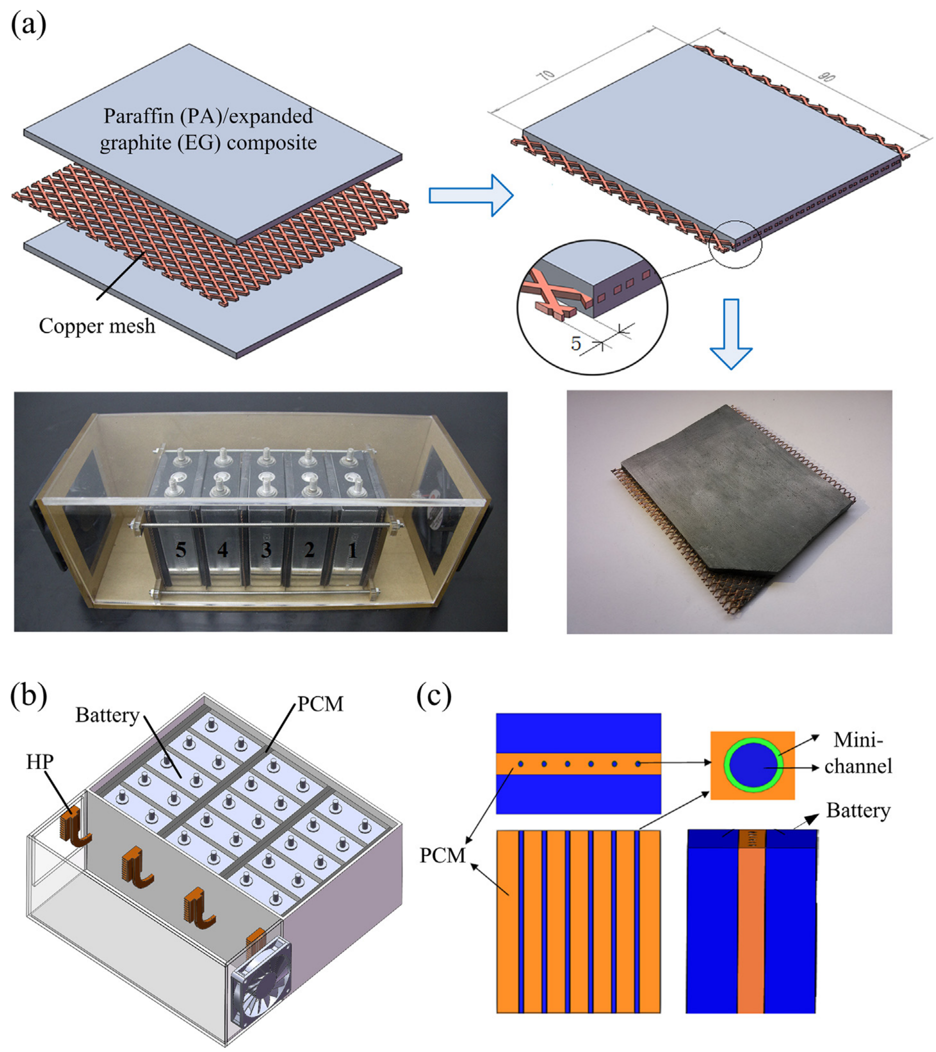


Fig. 5. PCM based BTM system coupled with (a) Copper mesh [136], (b) HP [137] and (c) liquid channel [138].

coolant and flowed through the micro-channels disposed in electrodes (Fig. 6(a)). Furthermore, a novel system that utilized an internal evaporator with micro-channels incorporated in a thick current collector (Fig. 6(b)) was investigated by Bandhauer et al. [141] and then applied to their follow-up study for side cooling [142] and edge cooling [143]. Subsequently, they proposed an internal BTM system with the mixture of multi-functional electrolyte and volatile co-solvents [144,145]. However, all these above cooling methods were performed for prismatic cells. For cylindrical cells, one potential method is constructing a through-hole inside the cell to form an axial fluidic channel (Fig. 6(c)) with liquid or gas as the coolant [146,147]. Axial cooling offers several advantages, while a larger channel result in more cooling performance at the expense of slightly reduction in cell capacity because of reduced volume [147]. It is emphasized that internal cooling method may not practical, but it should be further explored for its relatively high cooling efficiency and low temperature gradient.

Regarding internal heating strategies, an alternative method is alternating currents (AC) (Fig. 6(d)) that can effectively heat cells via I^2R losses without a substantial change of SOC [148,149]. The AC heating technology can be achieved by different waveform such as square-wave [150,151] and sinusoidal [152]. Stuart and Hande [153] proposed AC to warm the cell directly rather than using external heaters and the relevant patent was applied [154]. In this method, the preformed heating rate increased with the increasing of signal amplitude, but the effect of signal frequency on the heating performance was not taken into account. To address this problem, Ruan et al. [155] proposed an effective strategy to analyze the optimal frequency. The results demonstrated that constant frequency was more promising than variable frequency for engineering realization and the optimal frequency could be evaluated according to the intermediate temperature. What is more, the influences of signal frequency, current amplitude and waveform on the heating rate were investigated experimentally [156].

More recently, Wang et al. [157] reported an “all-climate battery” (ACB) cell which could heat itself up from subzero temperature without requiring electrolyte additives or external heating devices. The generic ACB structure is shown schematically in Fig. 6(e). Apart from the essential components (i.e., cathode, anode and electrolyte), a 50 μm-thick foil of nickel is introduced, which is electrically connected to the negative terminal on one end and creates a activation terminal outside the cell on the other. There is a switch between the negative and activation terminals which is driven by a temperature sensor. When the switch turns on at low temperature, electrons start flowing and substantial ohmic heat caused by Ni foil is generated to rapidly warm up the cell. Once the temperature reaches or exceeds 0 °C, the switch turns off and reverts the cell to a traditional one with low internal resistance. The results demonstrated that the ACB cell could rapidly self-heat from −30 °C to 0 °C within 30 s and thereafter delivered about 10-fold the power boost of state-of-the-art cells, with only ~5.5% of cell energy consumed (Fig. 6(e)). For 3 C quick charging test, the time to charge to 80% SOC of ACB showed a significant drop as compared to

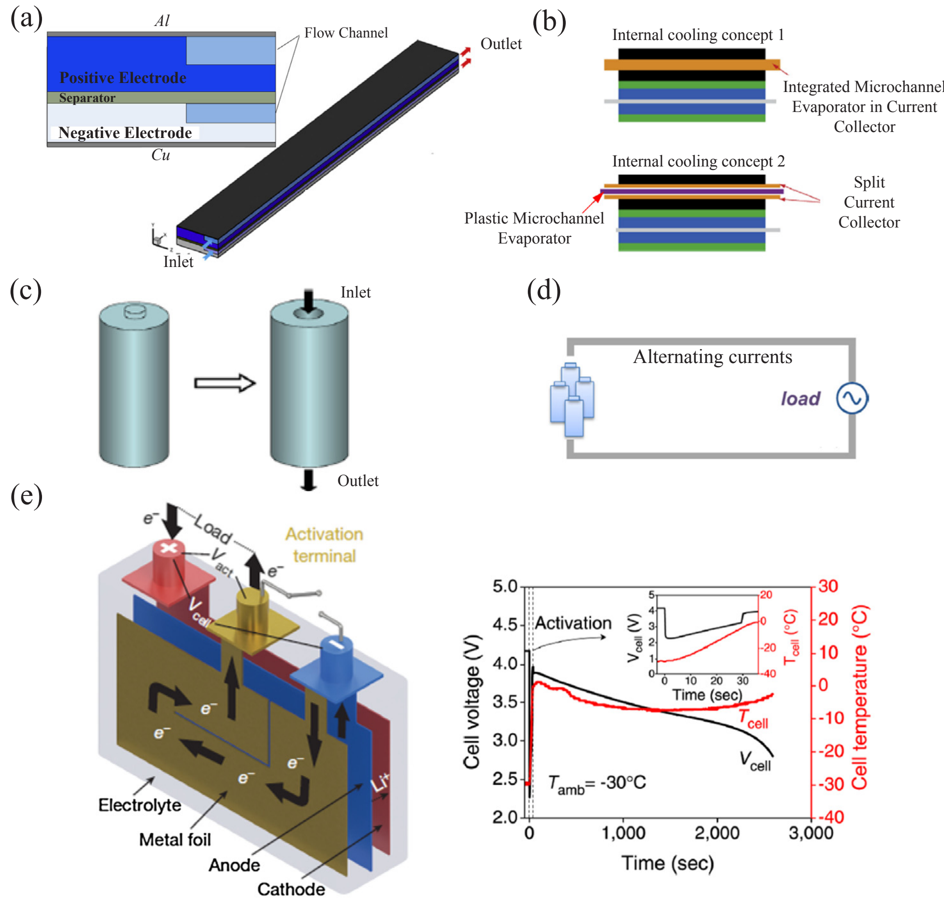


Fig. 6. Internal thermal management strategies: (1) internal cooling by (a) microchannel in electrode [140] and (b) microchannel evaporator in current collector [141] and (c) axial fluidic channel [146]. (2) internal heating by (d) AC heating [150] and (e) ACB cell [157].

conventional battery (14 min *vs.* 160 min) at a low temperature of −30 °C [158]. Further, an thermal-electrochemical coupled model was developed for computational design to study the key design factors with the highest self-heating efficiency [159].

5. Liquid based battery thermal management strategies

Generally, the liquid based BTM system has a relatively high heat transfer coefficient and can be divided into direct-contact mode and indirect-contact mode according to whether the battery surface is in direct contact with the heat transfer fluid (HTF).

5.1. Direct-contact mode

Direct-contact liquid based system usually use dielectric HTF to remove the heat from batteries efficiently with the advantages of greater compactness and higher cooling rate compared to indirect-contact liquid based system and direct air based system [160]. Park and Jung [101] developed a direct-contact cooling system for cylindrical battery modules and numerically studied the effect of HTF types (i.e., Air *vs.* Mineral oil) on the thermal performance of the system. The results showed that a wide battery module with small space between cells was preferable for the air based system, while a narrow module was desirable for a liquid based system because of the higher heat capacity of liquid. In addition, the air based system consumed much more power than liquid based system. Similarly, different HTF types (i.e., air, silicone oil and water) were applied by Karimi and Dehghan [161] to study the thermal performance of a high-power battery pack with different inlet-outlet configurations. When liquid flows through the cell surface, the convective heat transfer coefficient is normally an order-of-magnitude higher than the traditional air system, giving rise to a relative high Bi number that exceeds the limit of 0.1. In this situation, a significant temperature gradient inside the cell would exit causing the classical lumped-parameter model inapplicable. To address this problem, a spatial-resolution lumped-parameter model was developed and showed that it was applicable for liquid based system even though $Bi \geq 0.1$ [162].

Due to the thermal conductivity of conventional liquid such as oil and water is relatively low, nanoparticles filled HTF can be used to further improve the thermal performance [163]. For instance, Al_2O_3-water nanofluid was employed for cylindrical batteries by Huo et al. [164], in which the average temperature could be decreased by 7% as compared to water based system. To optimize the performance of direct-contact liquid based system, the HTF should has some essential characteristics such as non-inflammability, high electric resistance and environmental friendliness. It is worth noting that the direct-contact mode with oil-immersion is a mature technology for transformer cooling, which may give some references to the design of BTM.

Recently, a new direct-contact BTM strategy has been developed by directly immersing batteries in liquid HTF without flow. This method uses the latent heat of vaporization for cooling, where the boiling point of HTF is close to the desirable working temperature of battery. The liquid ammonia [165] and propane [166] were used as the HTF to construct a boiling cooling system by Al-Zareer et al. They found that this kind of system offered a unique opportunity to maintain the operating temperature of battery in an optimum range for the liquid-gas phase change at high discharge rate. Van Gils et al. [167] designed and experimentally investigated a pool boiling system (Fig. 7(a)), in which a

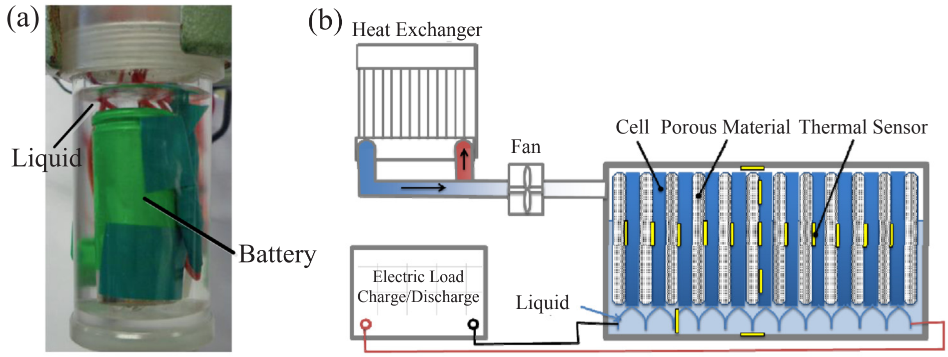


Fig. 7. Boiling heat transfer system: (a) battery monomer [167] and (b) battery module [168].

Table 5
Properties of HTF [168].

Properties	Novec™ 7000	Novec™ 649
Boiling point@1 atmosphere (°C)	34	49
Thermal conductivity ($W\,m^{-1}\,K^{-1}$)	0.075	0.059
Latent heat of evaporation (KJ/Kg)	142	88
Volume resistivity (Ω-m)	1.0×10^{6}	1.0×10^{11}

cylindrical battery (Sony US18550VR) was fully submerged in liquid (Novec7000) with a boiling temperature of 34 °C at atmospheric pressure. The liquid extracted heat from the battery and then started to boil and release thermal energy through the escaping vapor which could be turned into liquid again in a condenser. The results showed that the proposed HTF, Novec7000, did not conduct electricity and could be applied directly on battery without additional sealing. In addition, the liquid based cooling capacity greatly exceeded that of air and improved the thermal performance even if boiling did not occur. Similar method has been reported in Ref. [168], which investigated the boiling liquid system in module-level with ten laminated Li-ion cells (Fig. 7(b)). Between cells, a spacer with porous material or microfiber cloth was placed to make the HTF and vaporized gas move smoothly. They tested two types of HTF with different boiling points and the specifications are shown in Table 5. The results showed that by selecting suitable HTF, the module temperature could be controlled around 35 °C during cycling test without any particular thermal control systems.

5.2. Indirect-contact mode

Despite the high thermal performance of direct-contact mode, the presence of a direct contact of the battery with the HTF may not be practical in battery packs [169]. In addition, indirect liquid based system is easier to implement and the HTF (e.g., ethylene glycol/water) has a lower viscosity than the dielectric liquid (e.g., mineral oil) in direct mode, leading to a much higher flow rate with a fixed pumping power [170]. Thus, indirect-contact mode has been widely proposed and investigated by passing the liquid through a channel, which can be a metal plate with built-in channels (cold plate) or discrete tube.

5.2.1. Cold plate

Cold plate is generally characterized by a flat shape metal plate with internal channels through which liquid HTF is pumped, and it can be inserted at three locations (Fig. 8): embedded into battery monomer [141], sandwiched between adjacent cells [171,172,173,174] or attached to the sides of battery module [175,176,177,178]. For the internal liquid based system, the channel size should be small enough to be incorporated in the battery components such as thick current collector and the channel walls must be chemically inert due to the complex chemical reactions (Fig. 8(a)). When the cold plates are sandwiched between adjacent cells, the criterion of a low-thickness cold plate is necessary to facilitate better vehicle integration (Fig. 8(b)). As the top portion of a battery module provides place for electrical connections between cells, the cold plates are commonly in heat-transfer contact with the side [160,175,179] or bottom [180,181,182] portions of the module. In this situation, the cells may be sandwiched between two heat spreaders to facilitate the heat transfer from module to the cold plates (Fig. 8(c)). For the flat shape of cold plate, it is easy to make this method the state of the art in prismatic cells and the applicability for cylindrical cells is low. Zhao et al. [183], on the other hand, designed a liquid system, in which cold cylinder was attached to the cylindrical cell so that HTF could remove the heat. In general, the cold plate system is expected to be able to provide structural support for cells and integrate into the battery box for the safety and space-saving considerations in EVs [180].

Obviously, thermal performance and the corresponding power consumption (in terms of the pressure drop) of cold plate based system can be optimized by adjusting the channels' configuration. Further, different channel designs and flow patterns are required based on the objective functions.

The cold plate channel configuration can be commonly classified as parallel design and serpentine design. Rao and coauthors [184] designed a cold plate based BTM system, in which the mini-channels were distributed in parallel and equidistantly (Fig. 9(a)). The effects of channel number, mass flow rate and flow direction on temperature rise and distribution were numerically investigated. Further, they constructed a cold plate with only one inlet and outlet configuration (Fig. 9(b)). The HTF flowed through the inlet and then divided into several parallel branches. The results showed that 5 branches were enough for a cold plate to reduce the battery temperature to a desirable range by increasing the mass flow rate, moreover, with the increase in channel width came in a reducing in energy consumption [185].

Jarrett et al. [186] studied a serpentine channel (Vortex shape) cold plate based BTM system (Fig. 9(c)). Design variables of the channel's geometry (e.g., its length, width and route) were modeled parametrically depending on the objective functions of average temperature, pressure drop and temperature uniformity with a fixed boundary condition. An improved work was performed later with consideration of the effects of varying boundary conditions [187]. Another type of serpentine design with U-shape channel (Fig. 9(d)) was studied by other researchers [169,175,179,188].

Regarding to the internal structure of channels, Jin et al. [170] deigned an ultra-thin mini-channel cold plate with oblique fin to cool the batteries of EVs. The segmentation of the oblique fin could maintain boundary layer to be re-developed periodically, thereby enhancing the thermal performance of cold plate. It was shown that the oblique structure had a higher heat transfer capability than the common straight channel.

5.2.2. Discrete tube

Contrast to the cold plate structure, the heat transfer between HTF

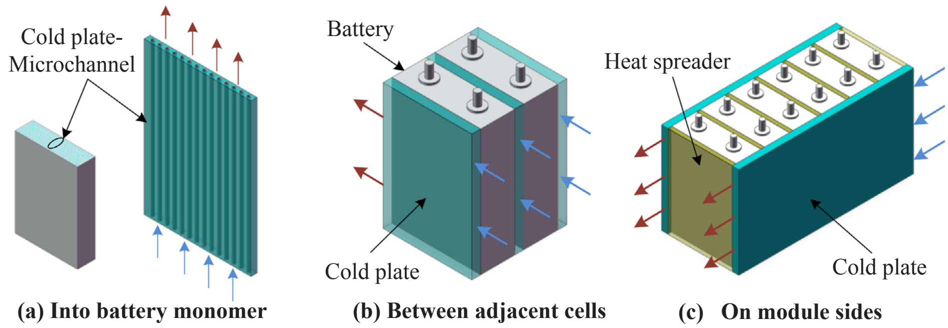


Fig. 8. Cold plate configuration with different locations.

and battery can be also achieved by installing discrete tube with different configurations. Lan et al. [189] designed a BTM system based on aluminum mini-channel tubes. Four different systems with different number of strips and mini-channels were applied to prismatic cells to study the effects of geometrical designs on cooling performance. Further, they investigated the influence of this cooling system on the TR behaviors in cell and module level, it showed that the mini-channel cooling could not cease the TR in battery monomer, but it could achieve the prevention of TR propagation in the module [190]. Gao and his coauthors [191,192,193] proposed a liquid heat exchanger structure based BTM system, in which flat tube banks were arranged on cell surface in staggered formation. Such a configuration might decrease the demands of flow path, fluid volume and total weight compared to cold plate structure. On account of the large latent heat of PCM and the high heat transfer efficiency of liquid, Rao et al. [138] proposed a coupled system with PCM stuffed into the space between aluminum tubes and prismatic batteries. It showed that the maximum temperature and temperature difference decreased with the increase of the number of tubes.

The indirect-contact mode with discrete tube is more applicable for cylindrical batteries. The BTM system in Tesla Model S has ribbon shaped metallic tubes in series that snake through the module to keep all the cells close the same temperature. The ribbon shaped tubes have a wave profile, which can get a greater portion of each cell to be in thermal contact with the tubes and a higher packing density of the battery pack, which can be found in Fig. 10. Different to the HTF tubes in series, Basu et al. [11] proposed a novel liquid based system that a set of aluminum conduction elements instead of liquid channels were attached to the cells in parallel (Fig. 11(a)). The generated heat was transferred from the cells to the conductive elements and then to the HTF on the side position. Such a configuration was expected to avoid the electrical connection of HTF even in the face of liquid leaks. In another study, a liquid based system based on discrete tubes and aluminum blocks with variable thermal contact surface was designed for cylindrical battery module as shown in Fig. 11(b) [194]. Similarly, a solid aluminum block or composite PCM was filled into the gaps between the cylindrical cells and copper tubes to study the influence of gap spacing on the propagation of cell failure in Ref. [181]. The results showed that the abundant heat from failure cell could be rapidly transferred to the HTF for aluminum block design, even under a close cell spacing configuration. For the integration of indirect-contact mode, it is essential to use good thermal conductivity materials in the packaging between the cells and the channel surfaces to enhance the heat transfer coefficient.

5.2.3. Heat transfer fluid

In an indirect-contact liquid based system, the HTF is conditioned using a heat exchanger and transported through the channels by a dedicated heating/cooling circuit. There have been a lot of studies on liquid based systems covering a broad range of HTF types. The typical used HTF are summarized in Table 6. Liquid water is mostly used as the HTF for its easily control and low cost. Nevertheless, the efficiency of single water based system is limited for its low thermal conductivity [198]. Therefore, a HTF with enhanced thermal conductivity and heat capacity is preferable, especially for the condition of higher heat load. It is well known that the thermal conductivity of fluid could be raised by

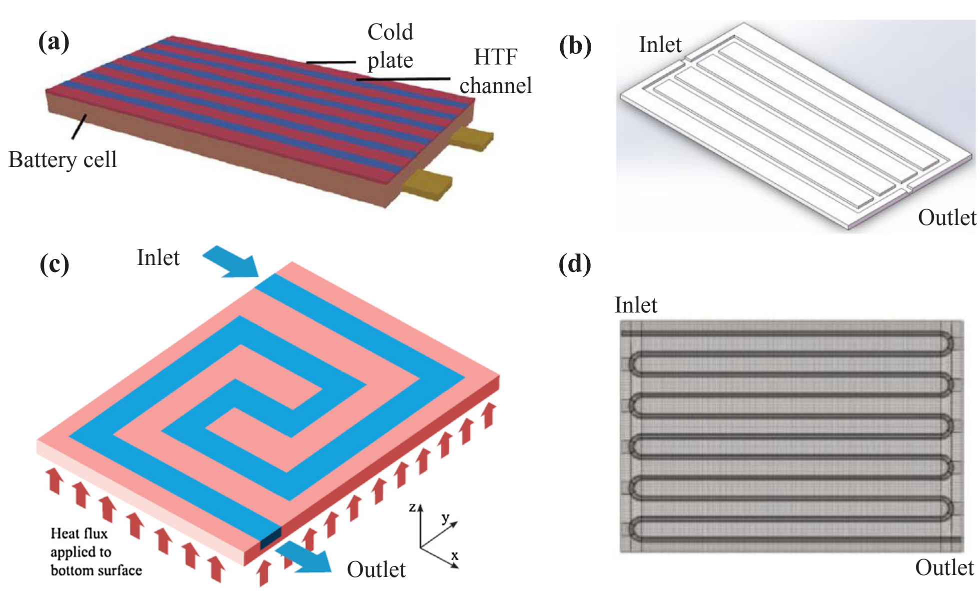


Fig. 9. Parallel: (a) [184] and (b) [185]; serpentine: (c) [186] and (d) [179].

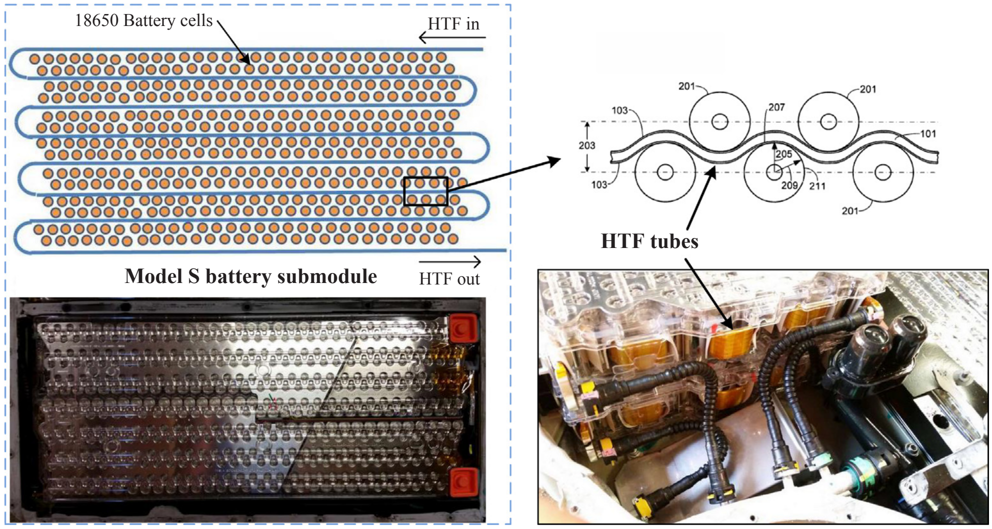


Fig. 10. Tesla Model S battery cooling (modified from [195–197]).

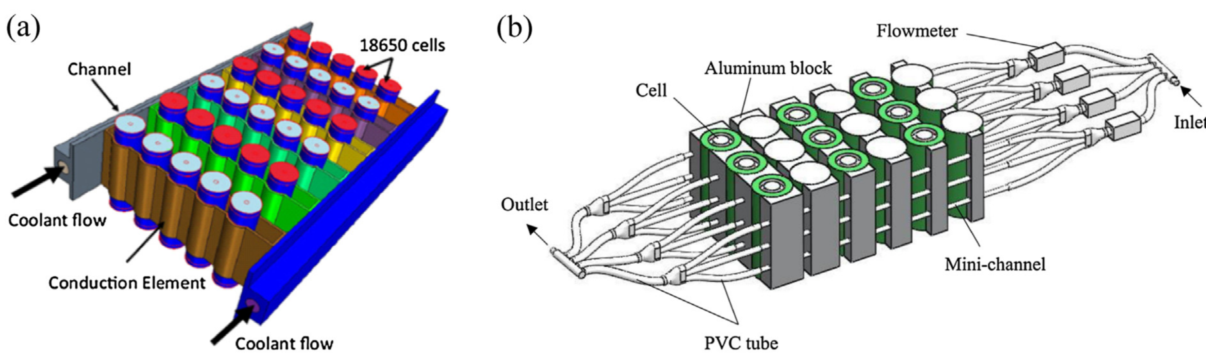


Fig. 11. Structure schematic of the BTM system (a) [11] and (b) [194].

adding nanoparticles, and the so-called nanofluid has been applied in many thermal management systems including BTM [164,199]. In Ref. [200], Hung compared nanofluid (Al_2O_3/water) with distilled water. Based on the experimental results, the enhancement of thermal performance was optimal at low concentration of Al_2O_3 (0.5%). Additionally, a new type of HTF, liquid metal, was presented by Yang et al. [198]. Because of the thermal conductivity of liquid metal is several dozen times higher than that of water, the liquid metal based system showed a much better thermal performance and less power consumption under the same flow condition (Fig. 12). What is more, the reciprocation flow of liquid metal could be easily formed by just changing the current direction of electromagnetic pump.

Another problematic aspect of using water as the HTF is that it will freeze under sub-zero climates. In the case of cold weather operating condition, the HTF is desirable with the function of anti-freeze. In this case, an efficient approach is to decrease the freezing point by adding anti-freeze materials to water. Almost all of these materials are from glycol family specially ethylene glycol, which is widely used for its water solubility. Additionally, the freezing point of the mixture varies with the ethylene glycol percentage. As can be seen in Fig. 13, when the ethylene glycol percent in water is 60%, the mixture does not freeze up to $-45\,^{\circ}C$. For the usage on automotive field at normal environment, the most common choice proportion of ethylene glycol and water is 50:50 [207]. Tesla and GM's BTM system use liquid glycol/water as the HTF to finish the heat transfer with a refrigeration cycle and heat the cells by electric resistance heating mode.

Recently, considering the high heat transfer coefficient of HTF during its liquid-vapor phase change, a passive thermal management method called refrigerant cooling was conducted [141]. In this refrigerant based method, the operation temperature could be controlled by changing the saturation temperature of HTF. However, the heat exchange part in this refrigerant based system is similar to the

Table 6
HTF in indirect-contact mode.

HTF	Reference
Water	Giuliano et al. [171]; Tong et al.[201]; Panchal et al.[172]; Basu et al. [11]; Rao et al. [138]; Lan et al. [189]; Qian et al.[185]; Huo et al. [184]
De-ionized water with sodium polyacrylate	Zhang [202]
Ethylene glycol-water	Jarrett and Kim [186,187]; Nieto et al. [175]; Jin et al. [170]; Saw et al. [160]; Chen et al. [169]; Smith et al. [203]
Mineral oil	Hosseinzadeh et al. [204]
Al_2O_3/water nanofluid	Hung et al. [200], Mondal et al. [205]
Liquid metal (Gallium, $Ga^{80}In^{20}$, $Ga^{68}In^{20}Sn^{12}$)	Yang et al. [198]
Novec 7000	An et al. [206]
R134a	Bandhauer and Garimella [141]

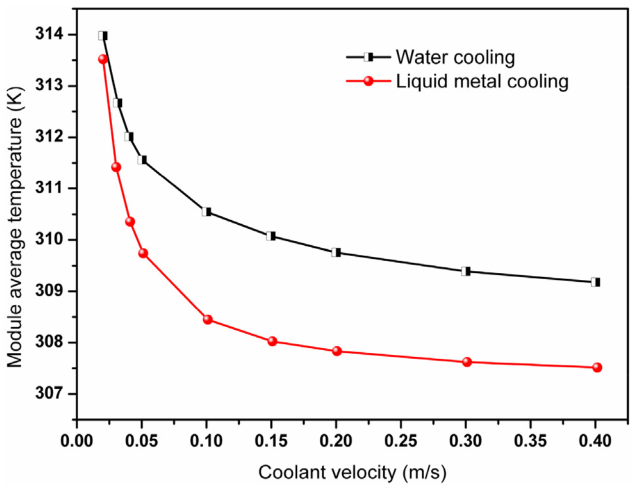


Fig. 12. Temperature variation of liquid metal system [198].

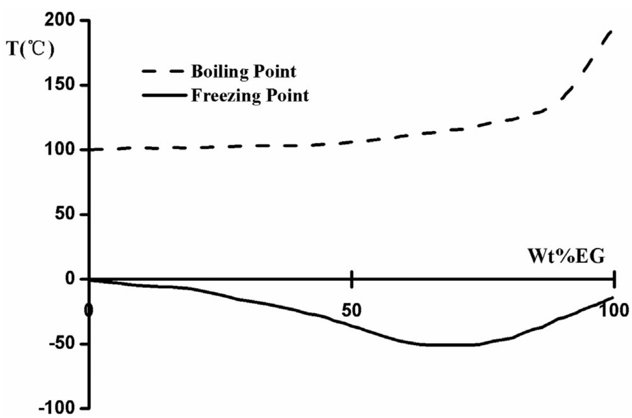


Fig. 13. Boiling and freezing point of water and ethylene glycol mixture [208].

evaporator of air conditioning system. It may not be able to heat the batteries in winter, and one possible approach is to adjust the refrigerant flow by switching the valves for cooling or heating.

5.3. Heat pipe based battery thermal management

HP, as a high-performance heat transfer component with excellent characteristics such as flexible geometry and compact structure, has been widely used in thermal management of various devices [209]. There are three major segments in a typical HP: evaporator, adiabatic and condenser sections. The heat source is attached to the evaporator section, which cause vaporization of the HTF, then transfer heat to the condenser section to decrease the temperature (Fig. 14). When the applications are executed for batteries, HP based BTM system has been fully studied experimentally [8,210,211,212,213,214] and theoretically/numerically [215,216,217,218]. Table 7 presents a chart for HP based BTM research works. By selecting a well-designed HP configuration with suitable working fluid, choosing the cooling method for condenser section, and changing the working conditions and orientations are among the approaches to improve the thermal performance of HP based system.

As HP can be of many size or shape, choosing a suitable HP is the first step to design a feasible and effective BTM system. A good thermal contact between battery and HP plays an important role in dissipating unwanted heat effectively. HP with flat evaporator section can achieve relatively higher contact area than tube shape HP when it is positioned on the battery surface [210,217]. To further cover the entire surface and enhance the heat transfer, HP can be also integrated within a metal plate for temperature flattening. The metal plate with HP set is generally inserted into the battery gap [8,215,216,227] or attached on module side [214]. In addition, flat HP [211] and flat plate loop HP [224] have the potential to be used in the BTM system for their flat surface. To fulfill the strict volumetric constraints, Zhao et al. [212] constructed an ultra-thin HP based BTM system, in which the thickness of HP was 2 mm and the evaporation section was sandwiched between two adjacent batteries. Hong et al. [222,230] proposed an ULHP with only 1.5 mm of wickless flat evaporator and investigated its availability for BTM system under various working conditions. Further researches related to the influence of different evaporator configurations and work angles on heat transfer performance have been also performed [231,232].

Besides the good thermal contact on evaporator section, adequate heat dissipation on the condenser section is another important aspect of a successful implementation of HP. Extended surface with finned array is the primary technology to augment the heat transfer area [89] and air is usually utilized as the cooling fluid to remove heat from the fin surface using fans. Such a system is simple but may cause the issues of bulky and noisy. Zhao et al. [187] proposed a HP based BTM system with four condenser cooling approaches, namely, natural convection, air forced convection, thermostat bath and wet cooling. Glycol-water mixture with higher thermal conductivity and specific heat capacity was used as the cooling fluid in contact with the finned array of HP by Wang [8]. In this way, the heat dissipation capacity could be improved, thus reducing the temperature with less volumetric flow. Also, the antifreeze performance of glycol-water mixture could make it possible for the practicality of battery heating even under sub-zero climates.

Generally, the degradation of thermal performance of HP could grow significantly worse under unfavorable inclination. Therefore, the

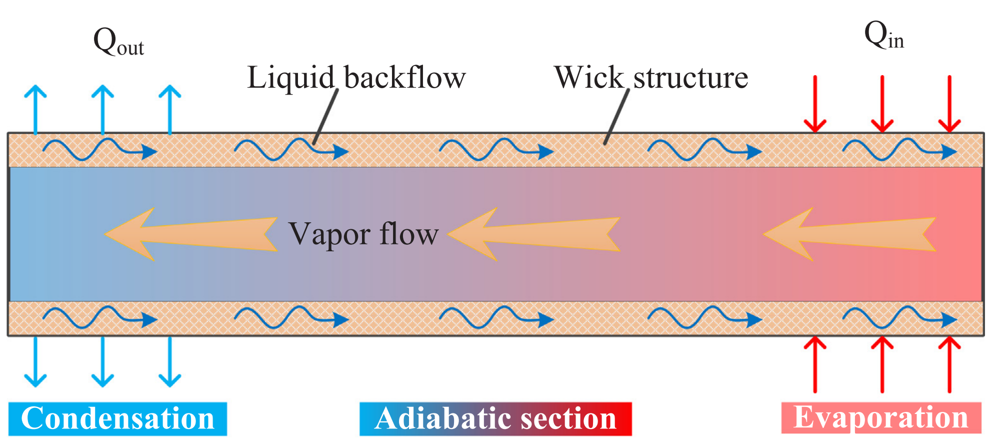


Fig. 14. HP working principle.

Table 7
HP based BTM research papers.

HP type	HTF	Condenser cooling source	Battery type (Heat source)	Research method	Variables	Reference
Pulsating HP (PHP)	Acetone; methanol; water; n-pentane; R134a	Air heat exchanger	– (Electronic with hybrid vehicle)	Experiment	Air temperature; air velocity; Angle of HP	Burban et al. [219]
Tube HP with flat evaporator section	Water	Thermostat bath	Prismatic (Electric heater)	Experiment	Heating power; Angle of HP	Rao et al. [210]
Tube HP	–	Constant T; Forced convection	Prismatic	Analytical and numerical simulation	Simulation model; Cooling solution	Greco et al. [215]
Bended Tube HP (120°)	Demineralized water	Adiabatic; Forced convection	Cylindrical module	Experiment	Fan inlet area; Angle of HP; Heating power; Air flow direction and velocity	Tran et al. [214]
Flat HP	Water	Heat sink with forced convection	Cylindrical module	Experiment	Heating power; Angle of HP	Tran et al. [211]
Oscillating HP (OHP)	Acetone	Thermostat bath	Prismatic (Electric heater)	Experiment	Heating power; Angle of HP	Rao et al. [220]
Tube HP	–	Finned array	Cylindrical	Simulation	Heat generation rates; Ambient temperature	Yu et al. [221]
Ultra-thin flat HP	Acetone	Natural convection; Forced convection; Water bath; Wet cooling	Pouch battery module	Experiment	Angle of HP; Cooling source; Spray frequency	Zhao et al. [212]
Ultra-thin loop HP (ULHP)	Water	Finned array with forced convection	Pouch battery module (Electric heater)	Experiment	Heating power; Fan power	Hong et al. [222]
L-shape tube HP with flat evaporator section	Water	Liquid box (glycol water mixture)	Prismatic (Electric heater)	Experiment	Heating power; Ambient temperature	Wang et al. [8]
Ultra-thin micro HP (UMHP)	Water	Finned array with forced convection	Prismatic module	Experiment; simulation	Discharge rate; HP arrangement	Liu et al. [217]
Tube HP	–	Forced convection	Cylindrical (Electric heater)	Experiment; simulation	HP size; Air flowrates; Heat power	Shah et al. [223]
Flat plate Loop HP (FPLHP)	Distilled water; alcohol; and acetone	Thermostat bath	Prismatic (Electric heater)	Experiment	Heating power; HTF types	Putra et al. [224]
Tube HP with flat evaporator section	Water methanol	Finned array with thermostat bath	Prismatic or pouch cells	Experiment simulation	Heating power; HTF types; Flow rat; Coolant temperature; Operating orientation; HP number	Ye et al. [213]
OHP	Acetone	Thermostat bath	Prismatic (Electric heater)	Experiment	Heating power; Angle of HP; Terminal direction	Wang et al. [225]
Loop HP (LHP)	Ammonia	Forced air convection (altitude cold air)	Cylindrical	Simulation	Discharge rate; HP configuration	Park et al. [226]
Tube HP	Water	Finned array with forced convection	Prismatic	Experiment simulation	HP layout; air	Yuan et al. [227]
Open-loop flat plate PHP	Ethanol	Cryostat with ethylene-glycol/water flow	-(Electric heater)	Experiment	Angle of HP; Heating power	Manno et al. [228]
Tube HP with flat evaporator section	Water	Cooling channel with water flow	Prismatic (Electric heater)	Experiment	Coolant flow rate; coolant temperature; start up time	Liang et al.[229]

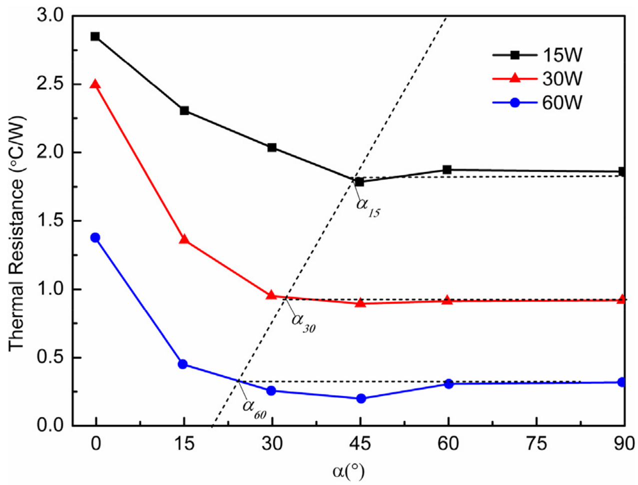


Fig. 15. Thermal resistance under different heating powers and installation angles [233].

evaluation of the HP based BTM system with different inclinations is necessary for EVs under downhill or uphill drive conditions. For example, the road slope is generally below 10% (5.71°) and inclined up to 37% (20.31°) [211]. Rao et al. [210] claimed that a best performance could be achieved when the tube HP with flat evaporator section was placed vertically (90°) compared to other angles. Similar results could be seen in other works for PHP or OHP based systems [138,219,220,228]. The condensate working fluid can be easily reflowed by gravity when the evaporator is at the bottom of the HP. The thermal resistance of HP is affected obviously by the installation angle, which can be found in Fig. 15 [233]. The thermal resistance could be reduced by strengthening the backflow with an improved internal structure of the HP. Wang [234] did a lot of work about HP based system in his doctoral dissertation, which performed a battery cooling and heating system via HP and claimed that HP with anti-gravity was desirable in BTM.

By taking into account the literature, it is easily found that the previous HP systems are usually based on prismatic batteries and few researchers have made efforts to improve the performance of cylindrical batteries. In addition, further works at module/pack level still need to be extended in the future.

5.4. Battery thermal management in vehicle thermal management

Generally, the heat source components in a vehicle have different ideal operating temperature ranges, which mean that various individual thermal management strategies are necessary. Further, the complexity of such more components may result in large cool/heat loading and power consumption. Therefore, establishing an integrated system has a lot of room for improvement in performance and energy-saving in vehicle operation process. Recently, vehicle thermal management (VTM) with subsystems integration such as heating ventilation air conditioning (HVAC) system and BTM system has get continuous improvement [191].

Carroll et al. [235] compared the cooling performance of series and parallel liquid coolant loops in a liquid based system. It showed that parallel loops provided a lower temperature difference in different modules, and a secondary cooling loop connected with HVAC system could be used for cold weather environments. Zou et al. [236] designed an integrated system for a five-chair EVs, in which the HP based BTM system was coupled with heat pump air conditioning system to construct a cooling/heating loop to facilitate HP heat transfer process (Fig. 16). This system could be switched by the refrigerant valves for

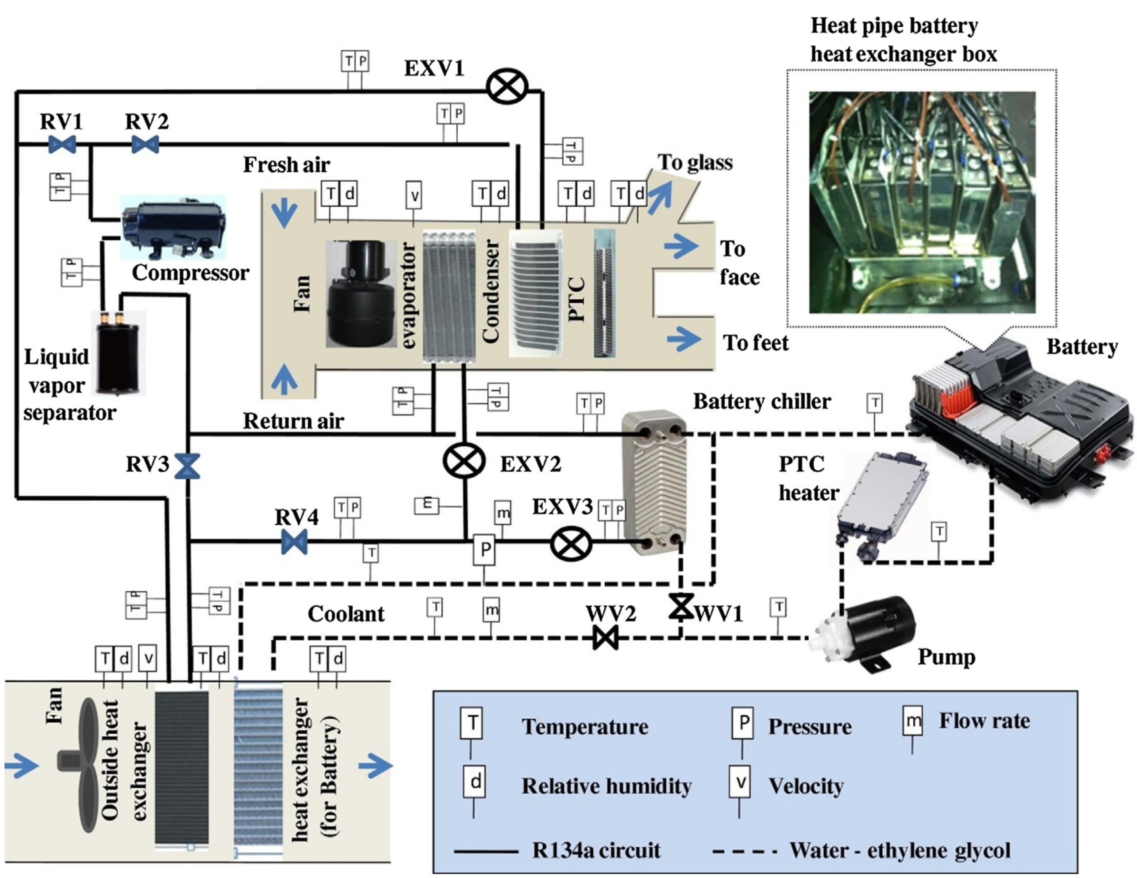


Fig. 16. Diagram of integrated system with BTM and heat pump [236].

cooling or heating. Hamut et al. [237] proposed three different BTM systems for EVs, i.e., active moderate liquid circulation with refrigerant, passive cabin cooling with air, and active liquid circulation with R134a refrigerant and water-glycol coolant. Because of the integration of an additional liquid cooling loop that connected to the refrigerant loop, the third method showed the lowest temperature rise, temperature difference and entropy generation rate.

For the different levels of sophistication in an integrated system, Tao [238] developed a strategy design to control the temperature inside the battery pack and other components of HEVs. The optimal strategy was effective to both improve the temperature tracking performance and reduce the parasitic power consumption. An integrated VTM system looped and functioned by liquid circulation was proposed by Zhang et al. [191]. This integrated system used HTF to transfer and allocate heat that came from different subsystems including BTM, HVAC and PCM thermal energy storage. The PCM storage was performed to recover the vehicle waste heat to support cold start and heating for batteries. In addition, the batteries could be cooled by coolant radiator or chiller according to the mild or extreme conditions. To reduce weight and volume, National Renewable Energy Laboratory (NREL, US) researchers performed a combined fluid loop technology that unified the cabin air-conditioning and heating, power electronics cooling, electric motors cooling and BTM into a single liquid coolant-based system [239]. This system had separate hot and cold fluid streams that were directed to the subsystems as required. It was expected that such a VTM system would be capable of exceeding 9% EVs range increase when the components and control strategies were optimized [240]. In summary, an integrated system with appropriate energy allocation and control unit can provide proper thermal performance and long life-span for EVs with the help of liquid circulation.

6. Conclusions

EVs and HEVs are environmentally-friendly and energy-efficient to meet the requirements of green and energy conservation with the help of green energy power source, namely, battery system. However, temperature could affect the reliability, safety and efficiency of the batteries. This review firstly illustrates the effects of temperature on battery performance from three aspects: low temperature, high temperature and differential temperature. Progress in scientific knowledge regarding battery model and simulation is positive to investigate the battery thermal behavior and assist designers to develop advanced battery thermal management (BTM) system.

An advanced BTM system can be categorized as internal and external system. The internal thermal management method may be effective but not practical. For external method, it can be summarized as air, liquid or phase change material (PCM) based system based on the employment of different heat transfer mediums. Although the air based system is safe and economical, it still suffers from low thermal efficiency. PCM can provide a suitable operating temperature, but some issues such as leakage and low thermal conductivity still exist and should be extended in much more detail.

Liquid based system has already been implemented in commercial EVs and HEVs because of its high heat transfer efficiency and compactness. Direct-contact mode has the advantages of greater compactness and higher cooling rate compared to indirect-contact mode, but it may not be practical in battery packs. The indirect-contact mode with cold plate and discrete tube is applicable for prismatic and cylindrical batteries, respectively. Liquid based system designs are expected to have less energy consumption according to the objective functions of pressure drop, temperature drop and uniformity. The thermal performance can be optimized by modifying the liquid channel configuration and heat transfer fluid characteristic. Applying heat pipe (HP) to BTM is worth of studying and the potential of novel HP for cylindrical batteries needs further research. Concerning the strict volumetric constraints in EVs, ultra-thin type of cold plate or HP is important to improve the overall performance, but investigation should be extended at module/pack level.

In addition, the liquid circulation is intended to facilitate the link between BTM and other thermal management systems in a vehicle. It is anticipated that the research, development and implementation of integrated systems from BTM to vehicle thermal management still need to be done further. Exploring the synergy mechanism of multi-thermal management subsystems has a great space in performance improvement and vehicle mounted energy saving.

Declaration of interests

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

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