A review on battery thermal management and its digital improvement-based cyber hierarchy and interactional network

Zhang, Y., Liang, F., Li, S., Zhang, C., Zhang, S., Liu, X., Zhao, S., Yang, S., Xia, Y., Lin, J., Guo, B., Cheng, H., Wang, M., Jiang, M. & Wang, D.

Original citation & hyperlink:
Zhang, Y, Liang, F, Li, S, Zhang, C, Zhang, S, Liu, X, Zhao, S, Yang, S, Xia, Y, Lin, J, Guo, B, Cheng, H, Wang, M, Jiang, M & Wang, D 2022, 'A review on battery thermal management and its digital improvement-based cyber hierarchy and interactional network', International Journal of Energy Research, vol. 46, no. 9, pp. 11529-11555.
https://dx.doi.org/10.1002/er.7957

DOI 10.1002/er.7957
ISSN 0363-907X
ESSN 1099-114X

Publisher: Wiley

A review on battery thermal management and its digital improvement based Cyber Hierarchy and Interactional Network （CHAIN）

Yulong Zhang [a], Fengwei Liang [a], Shen Li [e], Cheng Zhang [d], Shifang Zhang [a], Xinhua Liu [b, *], Shupeng Zhao [a, *], Shichun Yang [b, *], Yuhua Xia [c], Jiayuan Lin [b], Bin Guo [b], Hanchao Cheng [b], Mingyue Wang [b], Meng Jiang [a], Dan Wang [a]

[a] College of Mechatronical and Electrical Engineering, Hebei Agricultural University, 071001, China
[b] School of Transportation Science and Engineering, Beihang University, Beijing 100191, China
[c] Department of Earth Science and Engineering, Imperial College London, London SW7 2AZ, United Kingdom
[d] Institute for Future transport and Cities, Coventry University Coventry, Coventry CV1 5FB, United Kingdom
[e] Department of Mechanical Engineering, Imperial College London, London SW7 2AZ, United Kingdom

Abstract

The temperature has a significant influence on the performance of Lithium-ion batteries (LiBs). Meanwhile, the heat generated accumulation in the battery can trigger the battery's thermal runaway. Hence, the battery thermal management system (BTMS) is essential to ensure the safe and reliable operation of the battery. This paper comprehensively reviewed key technologies of BTMS and proposed a novel digital solution to improve the battery system performance. Firstly, the heat generation mechanisms and the thermal models were reviewed. Then this paper focuses on a review of liquid cooling thermal management methods. simultaneously, the solid-liquid phase change gas-liquid phase change is also summarized in the phase change material cooling system, and a summary is presented for the existing novel phase change cooling systems. Additionally, the preheating methods to heat the LiBs at low temperatures and the emergency battery thermal barriers upon thermal runaway were discussed. Eventually, a new approach for the BTMS leveraging from the Cyber Hierarchy and Interactional Network (CHAIN) framework is indicated and constructed the digital twin reflecting physical battery to improve the LiBs temperature control strategies. Besides, this paper provides a new direction for the design of BTMS through vehicle-side sensing, edge computing, and cloud-based digital twin three levels.

key words

Lithium-ion battery; Heat generation mechanism; Battery thermal model; Battery thermal management system; Emergency battery thermal barrier; Cyber Hierarchy and Interactional Network; Digital-twin

Nomenclature

q	Heat generation rate, $j \cdot s^{-1}$	ρ	Density, $kg \cdot m^{-3}$
I	Electric current, A	κ_D	Electrolyte phase diffusion conductivity, $\Omega^{-1}cm^{-1}$
U	Open-circuit voltage, V	λ	Thermal conductivity, $W \cdot m^{-1} \cdot K^{-1}$
V	Cell voltage, V	α	Degree of conversion
T	Temperature, K	***Superscripts***	
j^{li}	Butler-Volmert current density, A cm^{-3}	*eff*	Effective
a_s	Active surface area per electrode unit volume, cm^2cm^{-3}	***Subscripts***	
R	Universal gas constant, J $mol^{-1}K^{-1}$	*e*	Electrolyte phase
C	Concentration of lithium ions, mol cm^{-3}, also dimensionless concentration	*s*	Solid phase
R_f	Film resistance on the electrodes surface, Ωcm^2	*n*	negative
A	Electrode plate Area, cm^2	*p*	positive
V	Cell potential, V	sei	solid electrolyte interface
x	the coordinate across the thickness of the electrode, cm	ne	negative-electrolyte
r	Radial coordinate, cm	***Abbreviations***	
t	Time.\, s	AC	Alternating current
D	Diffusion coefficient of lithium species, cm^2s^{-1}	BTMS	Battery thermal management system
R_s	Solid active material particle radius, cm	CHAIN	Cyber Hierarchy and Interactional Network
F	Faraday's Constant, C mol^{-1}	DC	Direct current
t_0^+	Transference number of lithium ion	EV	Electric vehicle
σ	Conductivity of solid active material, $\Omega^{-1}cm^{-1}$	EIS	Electrochemical impedance spectroscopy
L	The thickness of cell, cm	EBTB	Emergency battery thermal barrier
C_p	Heat capacity, $J \cdot kg^{-1} \cdot K^{-1}$	HEV	Hybrid electric vehicles
v	Velocity, $m \cdot s^{-1}$	HP	Heat pipe

H	Total enthalpy, $kJ.\ k\ g^{-1}$	HDMR	High dimensional model representation
W	specific content in jellyroll, kg/m^3	IOT	Internet of things
Q	Heat generation rate, $j \cdot s^{-1}$	LiB	Lithium-ion battery
a	frequency factor, 1/s	OHP	Oscillating heat pipe
z	Dimensionless solid electrolyte interface (SEI) thickness	OCV	Open-circuit voltage
E	activation energy, J/mol	OBC	Olefin block copolymer
b	battery	P2D	Pseudo 2 dimensional
Greek symbols		PCM	Phase change material
α_a, α_c	Anodic and catholic charge transfer coefficients	PDE	Partial differential equations
η	Surface overpotential of an electrode reaction, V	SOC	State of charge
ϕ	Volume averaged electrical potential, V	SEI	Solid electrolyte interface
ε_e	Electrolyte phase volume fraction	TR	Thermal runaway
σ	Conductivity of solid active material, $\Omega^{-1}cm^{-1}$	TEG	Thermoelectric generators
δ	Thickness, cm	TEC	Thermoelectric cooler
κ	Electrolyte phase ionic conductivity, $\Omega^{-1}cm^{-1}$		

1. Introduction

With fossil fuel leading to environmental pollution and the exhaustion of non-renewable energy sources, increasing interest has focused on electric vehicles (EVs) and hybrid electric vehicles (HEVs)[1]. Lithium-ion batteries are the most popular power sources in EVs due to their advantages, such as high energy density, high power density, and low self-discharge rate[2–4]. Nevertheless, the performance and safety of LiBs are very sensitive to temperature[5]. Low temperature significantly reduces the performance of LIBs. Therefore, there are still some problems to apply LiBs in cold climate areas, such as reduced driving range and battery life [6–8]. High temperature also has some detrimental effects on battery performances including accelerated capacity, power, and energy losses [9–11]. In addition, the more serious consequence of high temperature is thermal runaway (TR) which could damage the vehicle and endanger passengers' life. So the BTMS is of great importance in achieving high performance and high safety of LiBs.

The battery thermal management has two critical issues, heat generation and heat dissipation. In terms of heat generation, different models have been developed, such as electro-thermal model, electrochemical-thermal model and lumped model. For heat dissipation, different BTMS are available, such as the air based, liquid based, phase change material (PCM) based cooling and hybrid cooling system. In general, the heat transfer medium used in BTMS mainly include air, liquid, PCM, and thermoelectric element. Air based cooling is the simplest method, which uses passive or active air flow to keep the battery within the optimal temperature range. There are numerous optimal design strategies to improve the air cooling efficacy. Optimizing the cell spacing can achieve more uniform airflow rates for the parallel air cooling BTMS[12], which obviously improves the cooling performance. The inlet and outlet locations for air based cooling system can be optimized to enhance the cooling performance. For example, experimental data indicate that the symmetrical inlet and outlet set in the middle of the plenums can achieve higher cooling efficacy for symmetrical BTMS[13]. Though air cooling systems have been widely used, the thermal conductivity of air is lower than other cooling medium, which limits its application in automotive. Fluid medium has higher thermal conductivity than air. Therein, the commonly used liquid mediums are water and ethylene glycol. Shang adopted the water and ethylene glycol as the coolant to design the BTMS for battery pack. Wherein, the flow rate is controlled to adjust the cooling rate. The BTMS has effectively restricted the maximum temperature rise of the battery[14]. In describing batteries, the discharge current is often expressed as a C-rate to normalize against battery capacity, which is usually very different between batteries. C-rate is used to measure the rate at which a battery is discharged relative to its maximum capacity. Chaithanya et al. conducted the cooling research on a 20Ah LiFePO4 battery using COMSOL software. The experiments were carried out by placing the cell between two mini-channel cold plates and conducting bi-directional coupled electrochemical-thermal simulations at different experimental conditions of discharge multiplicity (1-4C) and coolant inlet temperature (15-35°C). Meanwhile, temperatures were collected at ten different locations on the cell surface, and it was found that the measured and predicted values were very close to each other and that the temperature difference between the two was due to the assumption of uniform heat generation in the Li-ion battery model (P2D). The experimental results show that the Li-ion battery model can be used to design battery management systems[15]. Sandeep Dattu Chitta et al. comparatively investigated temperature prediction accuracy for a 20Ah LiFePO4 battery sandwiched between mini-channel cooling plates based on two different simplified cell models (Lumped and 1D electrochemical) models. Ten other locations on the cell surface were selected under different experimental conditions of discharge rate (1-4C) and coolant inlet temperature (15-35°C), and the temperature changes during discharge were compared. The experimental results found that the difference between the Lumped model predicted temperature and the 1D electrochemical predicted temperature was 2.1% at the 1C discharge rate; however, the difference increased to 16.4% at the 4C discharge rate, which is because the Lumped model ignores the cell's internal chemistry and is therefore recommended for the initial design of the BTMS[16]. There are some ways to improve the fluid thermal conductivity, e.g., by adding solid particles to the coolant. Experiments indicated that adding the different volumetric fractions of nanoparticle (Fe_2O_3) to the coolant (water and ethylene glycol) can improve fluids thermal conductivity[17]. The advantages of liquid BTMS include high cooling efficiency, high reliability and high heat capacity. However, one major disadvantage is that it increases the cost and complexity of BTMS due to the pump and other accessories. This can be problematic for small electric cars with limited interior space.

PCM-based BTMS can be used to address the liquid cooling issues of cost and complexity, because it doesn’t require an extra power source. PCM is generally filled in the gaps between cells[18,19]. V.G. Choudhari et al. investigated the thermal performance of a battery module containing 5x5 Li-ion cells arranged in series and parallel using phase change materials. Four different fin structure layouts, such as Type I, Type II, Type III, and Type IV, were experimentally proposed to improve the cells' internal heat dissipation, and the maximum and average temperature distributions in the battery pack were analyzed. The results show that the type III fin structure can minimize the internal heat build-up. At the same time, the experiments found that the convection effect can reduce the maximum temperature inside the cell and restore the melting fraction of PCM by investigating the impact of convection on the thermal performance of the cell[20]. When the battery temperature is high, PCM can absorb heat from the cells to limit the maximum temperature rise. The stored heat in the PCM can be released when the battery's temperature drops below liquid-solid phase transition point, e.g., as the vehicle travels at night. The advantage of the PCM-based BTMS include broad range of suitable phase change temperature, no consume parasitic energy and low cost[21]. However, one disadvantage is that the latent heat of PCM is limited, so it cannot absorb too much heat. Battery spacing is a key to the performance of PCM based BTMS. As the battery spacing increases, more PCM can be filled in the gaps, which can improve the thermal control efficiency. The hybrid BTMS design that combines PCM/oscillating heat pipe (OHP) also can solve the limited latent heat of PCM[22]. Another disadvantage of PCM-based BTMS is that the leakage of melted PCM also brings some detriment, such as environmental pollution and battery TR[23] .

Thermoelectric element based BTMS has gradually attracted people's attention owing to the high efficiency. No chemical coolant is used, which avoids leakage problems. A calibrated model of thermoelectric element based BTMS was developed in [24] to investigate its performance. The result indicated the thermoelectric element cooling method can cool the cell with high efficiency and keep a more homogeneous temperature distribution inside the battery module. Cai et al. adopted thermoelectric element cooling in combination with air cooling or liquid cooling that could achieve effectively and actively cooled[25].

In general, BTMS has a three-layer design concept. Firstly, it should ensure the battery operates within the optimal temperature range. Secondly, it should be able to sense the critical edge of battery malfunctions and send the alert information. Finally, once the thermal runaway happens, the relevant measures can suppress thermal runaway propagation effectively[26]. Kanishka Vikram Purohit et al. investigated the soft sensor for a battery pack system based on a two-layer feed-forward artificial neural network, by which the soft sensor was able to accurately estimate the state of charge (SOC), state of energy (SOE), and power loss of the battery pack. The prediction accuracy of the soft sensor is also compared with linear or non-linear regression models and parametric structure models for system identification. The accuracy of the soft sensor is 99.96%, 99.96%, and 99.99% for the battery pack SOC, SOE, and PL test datasets, respectively. It shows that the soft sensor has a higher prediction accuracy[27]. However, the most previous research on battery thermal management methods has focused on model simulation and experimental validation to optimize the thermal management system materials, structure and physical parameters (flow rate, latent heat, viscosity etc.). They have not further combined with the existing artificial intelligence, big data, models, and control algorithms to realize a whole life cycle battery thermal management strategy. Therefore, on the basis of summarizing the existing thermal management methods, this paper proposes a new digital solution, namely the full lifecycle BTMS based on CHAIN, which can be achieved by machine learning, big data, and model fusion etc. This review summarizes the heat generation mechanisms, thermal models, and thermal management methods of LiBs, and proposes a novel strategy that combines battery thermal management with cloud computing.

This paper is organized as follow. The heat generation mechanism and heat transfer model of LiBs are presented in Section 2. The three major applications of battery thermal management in EVs are reviewed in Section 3. The major applications are classified as cooling methods, battery preheating at low temperature, and emergency battery thermal barrier, which will be given in Section3.1, 3.2, and 3.3

separately. Section 4 presents a novel approach for the full-lifetime BTMS leveraging from the CHAIN framework, which helps to perfect the temperature control strategy of LiBs. Finally, the conclusions and directions for future research are given in Section 5.

2. Heat generation mechanisms and thermal models of LiBs

Heat generated inside LiBs mainly includes reaction heat, polarization heat, and joule heat[28]. Under abuse conditions, e.g., when the battery's temperature is too high, a large amount of heat can also be generated by side reactions, such as electrode decomposition[29]. In the worst case, with the accumulation of heat generated from the side reactions, the battery temperature will rise sharply, which eventually will result in TR.

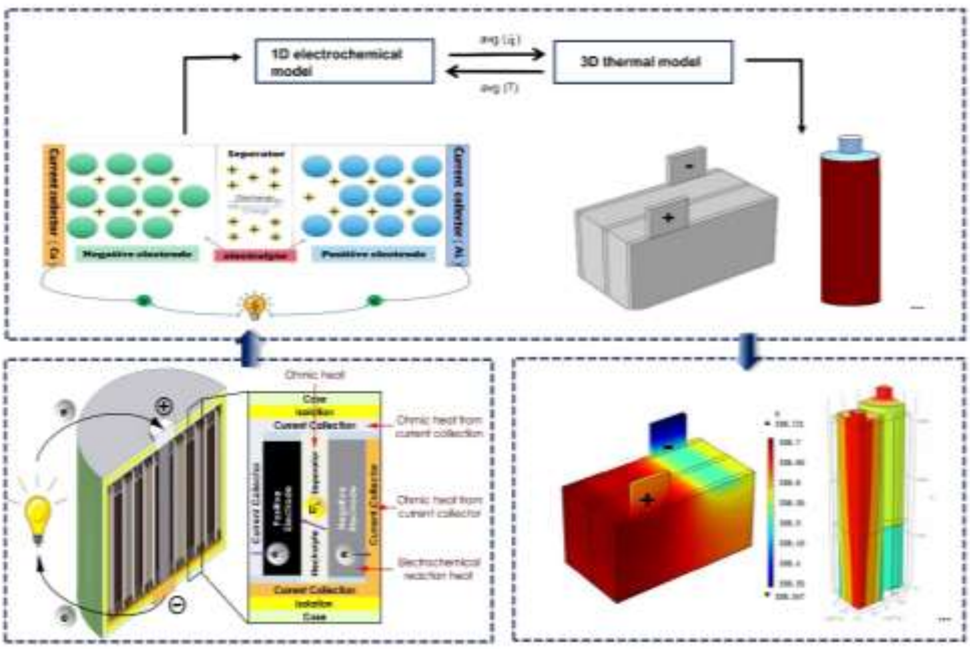

FIGURE 1 Heat generation mechanisms and thermal models of LiBs[30–34]

A battery thermal model describes the heat generation and dissipation processes inside the battery as well as the temperature response. Common thermal models based on the physical mechanisms include the electro-thermal model, electrochemical-thermal model, and TR model. In additional, these models based on the dimensions can divide into the lumped model, 1D model, 2D model, and 3D model[35]. The following section introduces the heat generation mechanisms and heat transfer models of LiBs, as it is shown in Fig.1.

2.1 Heat generation mechanism

The performance of LiBs is greatly influenced by temperature. Therefore, it is crucial to grasp the internal heat generation mechanism of LiBs[36,37]. Under normal working conditions, the internal heat generation of LiBs is usually inevitable due to electrochemical reactions during charge and discharge cycles, and also affected by environmental conditions; in the case of thermal runaway, the heat generation of LiBs comes from the undesired side reactions at high temperatures. The categories of heat generation and dissipation within the battery system are depicted in Fig. 2. The open-circuit voltage (OCV) variation with temperature leads to the entropy change, producing the reversible heat [38]; the irreversible heat mainly includes the polarization heat, the heat of mixing, and the phase transition enthalpy. The polarization heat is the heat loss caused by the ohmic polarization, the activation polarization, and the concentration polarization. The heat of mixing comes from the formation and relaxation of concentration gradient during the operation of LiBs. The heat of mixing in the porous electrode can divide into four modes: 1) concentration gradient distribution in spherical particles; 2) concentration gradient distribution in the bulk electrolyte; 3) concentration gradient distribution in the electrolyte within the pores of the electrode; 4) concentration gradient distribution in the bulk electrode. Finally, the phase transition enthalpy that lithium ions insert and de-insert the electrodes lead to entropic changes inside the electrodes is also one of the components of irreversible heat [34,39].

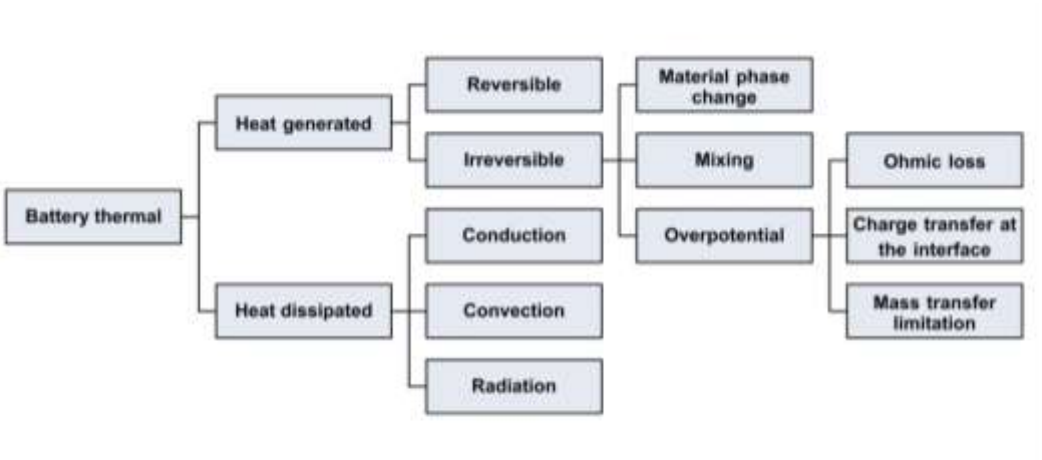

FIGURE 2 Summary of battery's heat generation and dissipation[40]

In the 1980s, Bernardi proposed a calculation model of the heat generation of LiBs assuming that the internal heating of the LiBs is uniform. In this model, the heat generation mainly divided into chemical reaction heat and ohmic heat generated by the internal resistance [41]. Additionally, they through experiment data simplified the LiBs heat generation equation as follows[42]:

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

q, I, U and V respectively represent the heat generation, the electric current, the open-circuit voltage and the cell voltage of the LiB. The establishment of this model laid a foundation for future studies of the heat generation rate of LiBs. Most computational models used for their following researches are the prototypes or evolutionary forms of this model.

It is an urgent need for battery thermal management to refine the heat generation mechanisms of LiBs at both cell, module, aging and TR levels, especially the non-uniformity of heat generation, and to clarify the heat generation law of LiBs in their full-lifespan. Doh et al. pointed out that the internal heat generation of LiB includes three parts, namely the ohmic polarization heat, the reversible heat, and the irreversible heat. He noted that the heat generation of LiBs mostly depends on the applied current, the internal resistance, the temperature, and the entropy of the battery and indicated a method to measure the entropy. The adiabatic slow cooling strategy was used to measure the variation of open-circuit cell potential with temperature, which could evaluate efficiently the entropy of LiBs[43].

Wang et al. studied the ohmic resistance, the polarization resistance, electrochemical impedance spectroscopy (EIS) and the heat generation of $Li_4Ti_5O_{12}$ within two different life cycles (One was cycled 2000 times at 55℃ and swollen， the other is a fresh one). The results showed that the ohmic resistance of the swollen cell was higher than that of the new cell, but the polarization resistance was more minor. The heat generated by the discharging process was greater than that caused by the charging process. In the process of single charge and discharge, the heating rate of the expansion battery was higher than the new battery[44]. The swollen cell released more reversible heat during the charging process, especially at a lower stage of charge. It is consistent with the studies of Giel et al. They pointed out that battery aging impacts on the calorific value and available capacity of LiBs under working conditions[45].

According to the internal resistance joule heating model, Yoo et al. derived a simple formula to calculate the irreversible heat of LiBs, which avoided the calculation of complex electrochemical reactions. EIS measurement performed at small intervals in the 0-10% and 90-100% State of charge (SOC) regions to capture the rapid changes of the internal resistance of the LiBs. The analysis showed that the reason for this rapid change is the intercalation of lithium ions into the electrodes. Furthermore, the heat generation of a full-scale battery pack that composed of 280 cylindrical cells was further analyzed. The analysis indicated that the temperatures of the tray predicted by the simulation are consistent with the experimental results. Thus, the feasibility of the thermal model for thermal analyses and the design of full-scale battery systems was confirmed[37].

Under battery abuse conditions, the heat generated from the side reactions is mainly produced after the TR. According to the order of reaction temperature rise, the side reactions of LiBs can classify as four categories: the decomposition reaction of solid electrolyte interface (SEI) film, the reaction of lithium with the binder in the anode material, the reaction of the cathode material with the electrolyte, and the decomposition reaction of the electrolyte[46,47]. Under routine runtime conditions, heat generated from the side reactions is so tiny that it can neglect.

2.2 Heat generation and heat transfer model of battery

Since the characteristics of LiBs are particularly sensitive to temperature, revealing the thermodynamics of LiBs is crucial. The thermal models are often applied to study the distribution of temperature fields in LiBs. The electrochemical model quantitatively describes the micro-physical and chemical processes in the LiBs from the principle, which not only can accurately simulate the external characteristics of the battery, but also can simulate the internal behaviors such as lithium-ion migration and diffusion in the electrode and electrolyte. The electrochemical model was first proposed by Doyle, Fuller, and Newman. Based on the theory of porous electrode and concentrated solution, they established the P2D porous electrochemical model[48–50]. In this model, it considered that the Lithium-ion transport between the anode and the cathode is one-dimensional during the discharging and charging processes. They are assuming that the active solid material is also composed of spherical particles. Meanwhile, a series of partial differential equations (PDEs) are used to describe the ion transport mechanism in the cell, the mathematical equations governing the charge and mass conservation in solid and electrolyte phases is discussed in details in [51] and summarized in Table 1[34].

wherein, the chemical dynamic reaction process inside the battery is described by the Butler-Volmer current density equation, it governs the volumetric rate of the chemical reaction and is can be followed as[52]:

$$j^{li} = a_s j_0 \left[\exp\left(\frac{\alpha_a}{RT}\eta\right) - \exp\left(-\frac{\alpha_c}{RT}\eta\right) \right] \quad (2)$$

Where the overpotential η is defined as:

$$\eta = \phi_s - \phi_e - U(C_{se}) \tag{3}$$

and the coefficient j_0 is a function of the surface electrolyte concentration C_{se} and obtained as:

$$j_0 = (C_e)^{\alpha_a}\left(C_{s,max}^{n,p} - C_{se}^{n,p}\right)^{\alpha_a}(C_{se}^{n,p})^{\alpha_c} \tag{4}$$

Finally, the cell potential, V, across the cell terminals is determined as follows [53]:

$$\mathrm{V} = \phi_s(x = L) - \phi_s(x = 0) - R_f\frac{I}{A} \tag{5}$$

The heat generation in cells mainly includes three parts, which can be followed by[54]:

$$q_o = \sigma^{eff}(\frac{\partial \emptyset_s}{\partial x})^2 + k_{eff}(\frac{\partial \emptyset_e}{\partial x})^2 + k_D^{eff}\frac{\partial \ln C_e}{\partial x}\frac{\partial \emptyset_e}{\partial x} \tag{6}$$

$$q_p = j\ (\emptyset_s - \emptyset_e - U_i - \frac{j}{a}R_{film}) \tag{7}$$

$$q_{rev} = -\frac{j_{int}T\Delta S}{nF} \tag{8}$$

Where q_o is the ohmic heat, q_p is the heat generated by the over potential and q_{rev} is the reversible heat. k_D^{eff} is the diffusional conductivity, n is the charge number of lithium ion and ΔS is the entropy change.

At present, the classical P2D model is widely used in studies such as battery aging mechanism, state estimation, and fast charging strategy. For example, Rahman et al. proposed a novel particle swarm optimization method to identify the specify parameters of a LiB based on the electrochemical model [55].

Table 1

Set of PDEs equations describing the P2D electrochemical model and its boundary and initial conditions[34]

Conservation equations	Boundary conditions	Initial conditions
Mass transfer in the solid phase		
$\frac{\partial C_s^{n,p}(x,r,t)}{\partial t} = \frac{D_s}{r^2}\frac{\partial}{\partial r}\left[r^2\frac{\partial C_s^{n,p}(x,r,t)}{\partial r}\right]$	$\left.\frac{\partial C_s^{n,p}}{\partial r}\right\rvert_{r=0} 0,$	$C_s^{n,p}(x,r,t_0) = C_{s_0}^{n,p}(x,r)$
	$\left.\frac{\partial C_s^{n,p}}{\partial r}\right\rvert_{r=R_s^{n,p}} = \frac{-j^{li}}{D_s a_s F}$	
Mass transport in the electrolyte		$C_e(x,t_0) = C_{e0}(x)$

$\frac{\partial \varepsilon_e C_e(x,t)}{\partial t} = D_e^{eff}\frac{\partial^2 C_e(x,t)}{\partial x^2} + \frac{1-t_0^+}{F}j^{li}$	$\left.\frac{\partial C_e^n}{\partial x}\right\|_{x=0} = 0,\ \left.\frac{\partial C_e^p}{\partial x}\right\|_{x=L} = 0$	$\phi_e(x,t_0) = \phi_{e,0}(x)$
Potential in solid electrodes $\sigma^{eff}\frac{\partial^2}{\partial x^2}\phi_s(x,t) = j^{li}$	$\left.\frac{\partial}{\partial x}\phi_s(x,t)\right\|_{x=0,L} = \frac{-I}{A\sigma^{eff}}$ $\left.\frac{\partial}{\partial x}\phi_s(x,t)\right\|_{x=\delta_n,\delta_n+\delta_{sep}} = 0$	$\phi_e(x,t_0) = \phi_{e,0}(x)$
Potential in electrolyte $k^{eff}\frac{\partial^2}{\partial x^2}\phi_e(x,t) + k_D^{eff}\frac{\partial^2}{\partial x^2}\ln C_e = -j^{li}$	$\left.\frac{\partial}{\partial x}\phi_e(x,t)\right\|_{x=0,L} = 0$	

Although the P2D electrochemical model could accurately describe the electrochemical behavior of LiBs, there is a lack of thermal behavior calculation and calibration of thermal model parameters. The thermal behavior of LiBs can be simulated by thermal models, for which the key is the calculation of the heat generation and the temperature field distribution. There are two main types of heat generation rate calculation models, namely the distributed heat generation model and the lumped heat generation model[56,57]. Based on distributed heat generation model and P2D electrochemical model, an electrochemical-thermal coupling model was proposed[58–60]. This coupling model not only uses the simulation results of the electrochemical model to calculate the heat generation rate and battery temperature, but also uses the calculated temperature to modify the thermal-related electrochemical parameters of the electrochemical model. The electrochemical-thermal coupling model mainly uses the Arrhenius equation (Eq. 9) or measured data to modify the thermal-related physicochemical parameters such as solid-phase diffusion coefficient, liquid phase diffusion coefficient, effective conductivity of the electrolyte, and the rate constant of electrochemical reactions[31,34,61].

$$\phi = \phi_{\mathrm{ref}}\exp\left[\frac{E_a}{R}\left(\frac{1}{T_{\mathrm{ref}}} - \frac{1}{T}\right)\right] \tag{9}$$

where ϕ and ϕ_{ref} are the values of the parameters under current and reference temperature respectively, R is the molar gas constant, T and T_{ref} are the thermodynamic temperature and reference temperature, E_a is the apparent activation energy.

The electrochemical-thermal coupling model describes the ohmic heat, polarization heat, and entropy of LiBs from the perspective of electrochemical reaction heat generation and mainly simulates the internal temperature of the battery under normal working conditions. Most of the electrochemical-thermal coupling models are based on the conservation of material and energy, assuming that the current distribution in battery is uniform. Due to the fact that the difference of current gradient inside the battery is neglected, these models are only suitable for small batteries to ensure the accuracy of the simulation results.

The electro-thermal coupling model is suitable for studying the thermal safety problems caused by the current inconsistency of LiBs. It is often based on the electrochemical-thermal coupling model to improve the accuracy of the model. Based on the principles of electron conduction, mass transfer, energy conservation, and electrochemistry, Ye et al. established an electro-thermal coupling model to predict the diffusion rate of lithium ions and the chemical reaction rate of cathode materials， which showed excellent agreement between the modeling results and experimental results[62]. Chen et al. established the electro-thermal coupling model of the battery pack and realized the accurate prediction of the battery pack temperature[63].

Multi-field coupling models were developed. Zhang et al. proposed a typical sandwich model for the mechanical-electric-thermal coupled simulation of LiBs. This model predicted the initial temperature of TR caused by mechanical extrusion. In addition, they also explored the evolution law of voltage and temperature caused by mechanical extrusion[64]. Yang et al. indicated an electrochemical-thermal-mechanical coupling model to study the aging mechanism of LiBs. Based on the previous electrochemical-thermal model, this model introduces the influence of mechanical stress on TR. The stress-stain equation is as follows:

$$\varepsilon_r = \frac{1}{E}(\sigma_r - 2v\sigma_\theta) + \frac{1}{3}\Omega C_s \quad (10)$$

$$\varepsilon_\theta = \frac{1}{E}[(1-v)\sigma_\theta - v\sigma_r] + \frac{1}{3}\Omega C_s \quad (11)$$

Where E is Young's modules, v is Poisson's ratio, Ω is the partial molar volume of the solute, ε_r and ε_θ are the radial and tangential strains, σ_r is the radial stresses, σ_θ is the tangential stresses. The model considered not only the side reactions of the anode but also the loss of active materials of the cathode. The aging behavior of LiBs under different discharge rates and ambient temperatures was studied using this model, which showed that the main reason for battery aging under high discharge rates is the loss of active materials [54].

Studies on the heat transfer of LiBs are mainly concerned with the temperature distribution inside the battery and the heat dissipation between the battery and the ambient environment. The heat transfer equation as shown in (Eq. 12)

$$\rho C_P\left(\frac{\partial T}{\partial t} + v_e \cdot \nabla T\right) \approx \frac{\partial(pC_pT)}{\partial t} = \nabla \cdot \lambda \nabla \mathrm{T} + \mathrm{q} \quad (12)$$

Therein, ρ expresses the average density of the battery. C_P expresses the average heat capacity under constant pressure. v_e is the electrolyte velocity. λ is the average thermal conductivity in all directions and q is the heat generation rate[30]. At present, most studies assume that the cell is solid, ignoring the heat transferred by the convection between the electrolyte and the porous electrode. The external heat conduction of LiBs mainly takes into account that the heat transfers between the LiBs and high thermal-conductive media, such as the heat transfer between the cold plate and the battery, and heat transfer between the cold plate and the cooling medium. Most studies ignore the radiation effect of LiBs on the ambient environment, which is reasonable since the actual battery pack is often surrounded by thermal insulation materials[65,66]. To study LiBs heat transfer, it is difficult to use analytical methods to solve the complex heat transfer process coupling multi-physical phenomena, such as solid heat conduction differential equation, Navier-Stokes equation, phase change, and soon. Therefore, the finite element method is often used to solve these problems. However, this method consumes massive computational resources and is not suitable for online applications[67,68]. Some scholars proposed the equivalent thermal resistance network model to study the heat transfer of the LiBs[69–72]. In this method, the similarity principle is used to simulate the physical processes with equivalent circuits. The amount of calculation is significantly reduced, but the distribution of the battery current field is often ignored. Hence the accuracy of the result is limited[73].

The thermal safety of LiBs limits EVs' applications. TR is often triggered by various abuse, including thermal abuse, electrical abuse, and mechanical abuse[74]. Some extreme environmental conditions may also cause high internal battery temperatures and trigger a series of side reactions. The accumulation of heat generated by the side reactions will make the temperature rise sharply, which then will further aggravate the process of side reactions and eventually lead to TR safety problems. The thermal abuse model plays a part in understanding the mechanisms of TR, improving vehicle safety, and TR warning. LiB thermal abuse models are generally based on the traditional electrochemical-thermal coupling model, along with possible TR side reactions and the associated heat generation within the battery. These TR thermal models can simulate and predict the evolution process of TR under the condition of thermal abuse. According to model proposed by Hatchard[75], the total heat generation rate of electrochemical side reactions during the thermal runaway process is approximately the Arrhenius equation as follows:

$$q_{de} = V\Delta H c^n A exp(-E_a/RT) \tag{13}$$

Where V is the volume of component substances of a LiB, $\Delta\mathrm{H}$ is the heat generated by electrochemical side reactions, C is the reactant's concentration involved in electrochemical side reactions, n is the reaction order, E_a is the activation energy, R is the universal gas constant, and T is the reaction temperature.

The common heat generation equations in the process of TR are summarized in Table 2.

Additionally, Qu and Rao et al. conducted in-depth researches in the field of thermal safety, and recently summarized the inducements of TR over a wide temperature range and also proposed relevant solutions[76]. Feng et al. introduced a TR propagation model, which is consistent with the experimental results and could provide corresponding solutions for suppressing TR[77]. To investigate the TR propagation behaviors in the battery pack, Jiang created a lumped thermal resistance network, which is based on the heat transfer characteristics of LiB packs. In their study, TR propagation features were discussed with different TR trigger locations, and the TR prevention effect of PCM was evaluated. The proposed prediction method shows a good ability to resolve the TR propagation problem [78].

Table 2

Thermal runaway reaction equation[79].

Reaction stage	Reaction temperature	Reaction equation
Solid electrolyte interface (SEI) decomposition	70℃	$Q_{sei}(T_b,\ C_{sei}) = H_{sei}W_{sei}a_{sei}exp\left(\frac{-E_{sei}}{RT}\right)C_{sei}$ $\frac{dC_{sei}}{dt} = -a_{sei}exp\left(\frac{-E_{sei}}{RT}\right)C_{sei}$
Reaction of negative-electrolyte	120℃	$Q_{ne}(T_b, C_{ne}) = H_{pe}W_{ne}a_{ne}exp\left(\frac{-E_{ne}}{RT}\right)exp\left(\frac{-z}{z_0}\right)C_{ne}$ $\frac{dC_{ne}}{dt} - a_{ne}\exp(\frac{-E_{ne}}{RT})\exp(\frac{-z}{z_0})C_{ne}$ $\frac{dz}{dt} = a_{ne}\exp(\frac{-E_{ne}}{RT})\exp(\frac{-z}{z_0})C_{ne}$
Reaction of positive-electrolyte	200℃	$Q_{pe}(T_b,\ C_{pe}) = H_{pe}W_{pe}a_{pe}\exp\left(\frac{-E_{pe}}{RT}\right)\alpha(1-\alpha)$ $\frac{dC_{pe}}{dt} = a_{pe}\exp\left(\frac{-E_{pe}}{RT}\right)\alpha(1-\alpha)$
Reaction of electrolyte decomposition	230℃	$Q_e(T_b,\ C_e) = H_eW_ea_eexp\left(\frac{-E_a}{RT}\right)C_e$ $\frac{dC_e}{dt} = -a_cexp\left(\frac{-E_e}{RT}\right)C_e$

3. Application of BTMS in EVs

BTMS has many components as shown in Fig.3, including sensors, controllers, actuators and the primary functions have rapid cooling, efficient preheating, TR treatment and communication etc. The goal of BTMS includes temperature reduction, uniform temperature distribution, reduction of energy consumption, economic costs, and improved safety. The function of BTMS plays a vital role because it can protect the battery by always maintaining a safe working range to reduce side effects such as battery power and capacity decline. The detailed data of the battery, such as terminal voltage and battery current, are captured by the cell monitoring function. The data collected in real-time can predict the state of the battery in the next stage[40]. In the following part of this section, which mainly introduces the application of thermal management in EVs, including cooling methods, preheating at low temperature, and TR treatment. Additionally, the comparison of several different thermal management technologies is summarized in Table 3.

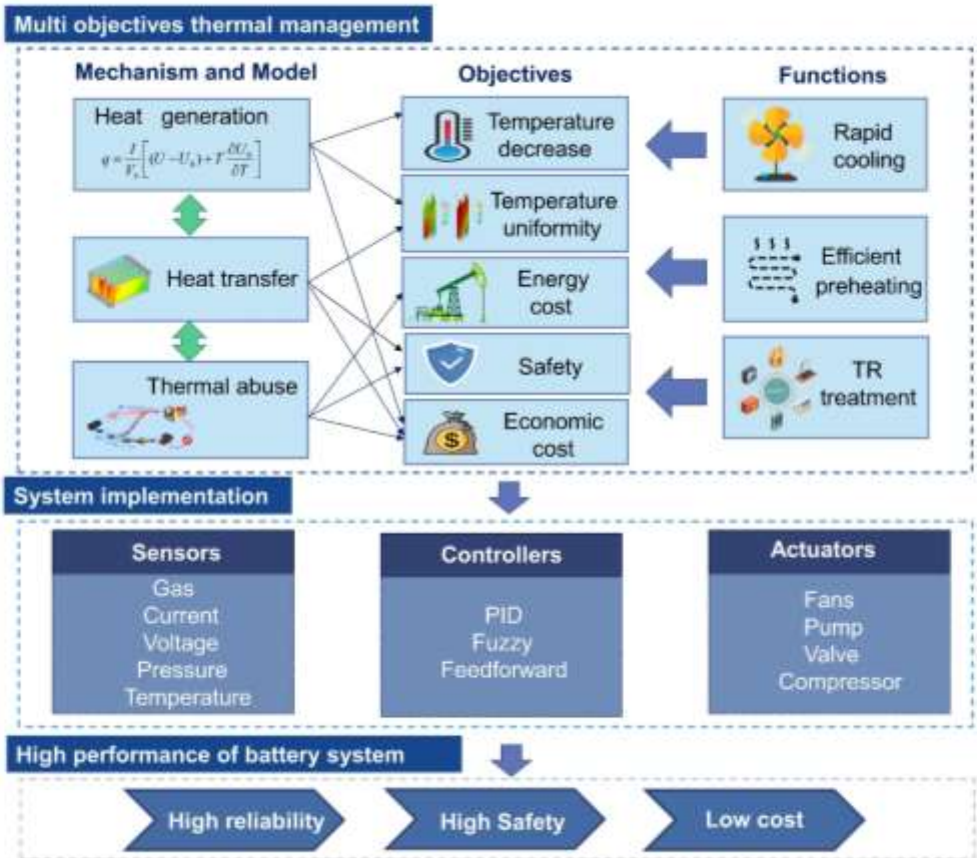

FIGURE 3 Multi-objective optimization scheme for BTMS[77,80,81]

3.1 Cooling methods

BTMS can divide into four categories as depicting in Fig. 4: air cooling, liquid cooling, PCM thermal management, and thermoelectric element cooling. PCM thermal management includes solid-liquid phase change, gas-liquid phase change, and heat pipe (HP) cooling. Air cooling mainly focuses on natural cooling and forced air cooling. Cooling of thermoelectric elements focuses on Peltier effect cooling.

3.1.1 Air cooling system

Air cooling has several advantages, such as simplified accessories, lightweight and convenient maintenance. It is because of these advantages in the field of EVs that air cooling systems have been widely used. [82], for example, Mazda Demio EV, Toyota Prius, Honda Insight, Nissan leaf, and BYD F3DM[40]. Nissan leaf pure EV adopts a passive battery pack thermal management system. With the optimized electrode design, the internal impedance of the LiB and the heat generation rate reduced simultaneously. At the same time, the thin layer (the thickness of the cell is 7.1mm) structure makes the heat inside the battery less to accumulate, which reduces the demand for the complex thermal management system[83]. The cooling capacity of the battery air cooling system can be significantly improved by integrating the battery air conditioning system with the vehicle air condition system. Yet, it needs to coordinate the different environment requirements of the battery and the passenger compartment. Tao et al. proposed a forced convection air cooling intelligent control thermal management system integrated with the vehicle air conditioning system. The system established a lumped parameter cylindrical battery thermal model and used Kalman observer to estimate the transient surface and internal temperature changes. The inlet cooling air temperature of the battery was optimized using the optimal control theory, and the model predictive controller was developed to adjust the refrigeration compressor in order to track the ideal cooling air temperature[84].

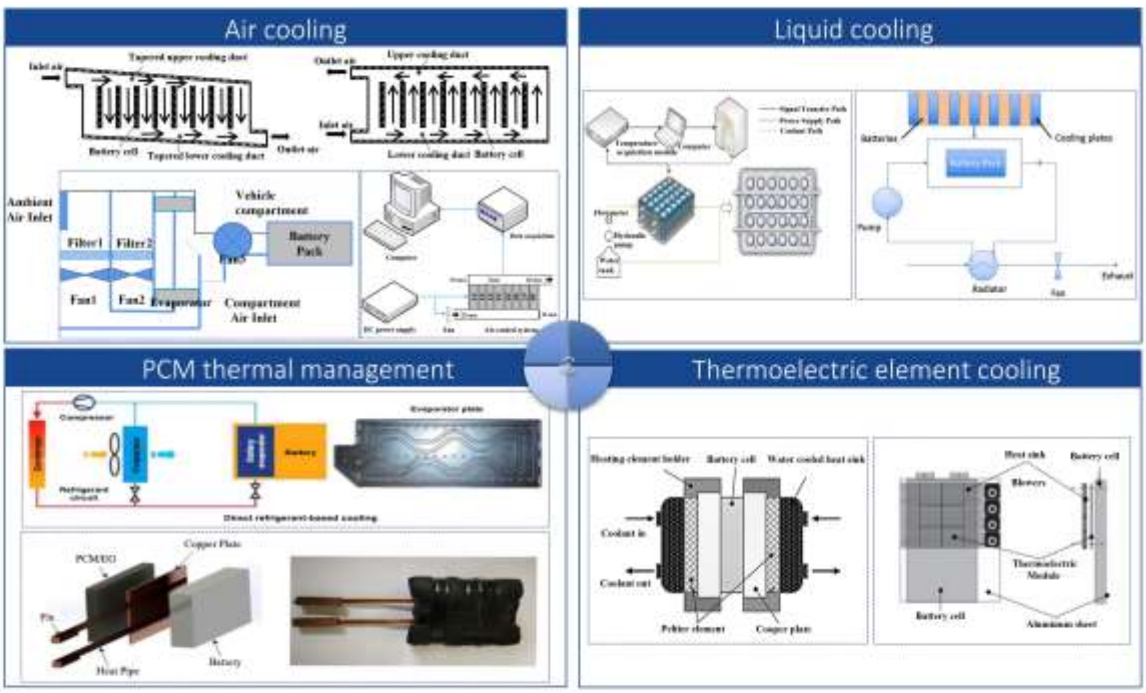

FIGURE 4 Cooling methods for LiBs[12,26,67,85–90]

3.1.2 Liquid cooling system

In the application of high-performance EVs, air cooling cannot meet the demand for high-power battery heating and cooling. Because the specific heat capacity and thermal conductivity of liquid are greater than that of air, the thermal management system with liquid as the medium has been widely adopted. In general, liquid-based BTMS has high thermal conductivity and can be classified into direct-contact and indirect-contact cooling according to whether the battery contacts the cooling medium directly[40]. The first method is mainly referring to immersing the battery in the cooling oil. This cooling method is widely used in electronic components. The second method is achieved via the contact of the battery with a cold plate filled with the cooling liquid for heat dissipation. In this way, the battery is cooled by the cooling cycle composed of the pump, valve, and pipeline. Although direct contact mode has higher thermal performance, direct contact between the battery and the cooling oil is not practical in vehicle battery modules. In addition, the viscosity of indirect contact coolant such as glycol/water is lower than that of the cooling oil. A higher flow rate can be obtained by the fixed pump. Therefore, the indirect contact method has been widely adopted and become the major cooling method for commercial EVs. Tesla EVs adopt a liquid cooling system, which uses rows of S-shaped cooling isolation plates to increase the contact area between the cells and the cold plate[91]. GM volt EV also adopts a liquid cooling method, which is a typical liquid cooling system configuration of the soft pack or square battery. In this system, between each pair of batteries arranged a cold plate, microchannel placed on the cold plate, and manifolds set on both sides to provide coolant for the cold plate. The pressure loss in the cold plate is much greater than the manifold pressure[92].

The research of liquid cooling systems mainly includes three aspects: cooling system configuration, heat flow control parameters, and new types of coolant. E et al. proposed a BTMS with a rectangular channel cold plate[93]. The modeling results showed that the best combination of parameters was: 45 mm for the channel width, 5 mm for the channel height, 4 for the channel number, and 0.07 m/s for the cooling liquid flow rate. On this basis, the average temperature and temperature difference of the cooling plate is the smallest. Mohammed et al. presented a dual-purpose cooling plate for prismatic batteries, which can prolong the service life and safety of batteries in vehicle applications[87]. The operating temperature of batteries can keep within a suitable temperature range through the cooling plate. On the one hand, the measure could increase the battery life. On the other hand, it could effectively control the heat generated during the TR. The system adopted a coolant with 60% ethylene glycol in water. Under the condition of 20°Cand 0.2L/min, the surface temperature of the battery could keep below 25°C. And it can control the temperature of the battery in the TR period in 30 seconds to about 75°C when the coolant is 20°C and the coolant flow rate is 30L/min. In addition, new cooling fluids such as nanofluids and metallic fluids have gradually attracted great interest from relevant scholars due to their advantages, such as high thermal conductivities and low power consumption. Kiani et al. selected three nanoparticles—alumina (Al2O3), copper oxide (CuO), and silver oxide (AgO) for the preparation of properly stable nanofluids to analyze the BTMS for pouch LiBs modules[94]. Test results demonstrated that the suspended particles in the nanofluid causes increasing in its thermal conductivity, hence, the existence of suspended particles in cooling fluid enhances the heat transfer efficiency. Although liquid cooling can control the temperature of LiBs effectively, its system design is more complex to protect the pack from liquid leakage and increases power consumption[95].

3.1.3 PCM cooling system

PCM brings convenience to the implementation of BTMS. It can absorb a lot of heat in the process of phase transition while keeping the phase change temperature unchanged for a long time[96,97]. This system has the advantages of passively buffering high temperatures and extending battery life[98]. Phase transition thermal management system can divide into solid-liquid phase change type and gas-liquid phase change type according to the PCM. The gas-liquid phase change includes direct cooling and HP cooling.

The solid-liquid PCM BTMS was first proposed by Al hallaj in 2000[99]. Many researchers have indicated that solid-liquid phase transition thermal management is an efficient and feasible low-cost thermal management technology[100–103]. When the battery temperature is below the phase transition point, the PCM can release heat to maintain the battery temperature, thus achieving thermal management. This method does not need additional circulating refrigeration equipment. However, the low thermal conductivity, the drift of phase change point, and the deformation caused by thermal stress after multiple thermal cycles of PCMs limit the application of the solid-liquid phase change method. To improve characteristic of thermal management, nanoparticles, fins and porous metal foam are adopted beside the PCM. With the two heat generation rates (4.6W, 9.2W), though comparing with adding nanoparticles into the PCM, using different numbers of fins, and employing the metal foam on the thermal management system performance are researched. The experiment found that the porous-PCM compound present more excellent cooling performance than the nanoparticle-PCM and fin-PCM ones, the average temperature of the cell decreased by 4K and 6K[104]. The other research applying PCM (n-eicosane) combined with nanoparticles volume fractions of 5% Al_2O_3 and three horizontal radial copper fins can obviously improve the melting time up to 28.3%, it greatly improves the issue of low thermal conductivity of the PCM[105]. Wu and coworkers showed an innovative and facile BTMS based on flexible composite PCM, therein, the composite PCM involving paraffin, olefin block copolymer (OBC) and swollen graphite. The OBC and swollen graphite was applied as the supporting component and thermal conducting component, respectively. The mentioned BTMS presented an excellent thermal control performance, When the battery is discharged from 100% to 0%, it shows higher cooling performance than that without PCM, particularly at high discharge rate (2.5C)[106]. The difference between thermal management using composite PCMs and traditional thermal management methods, the thermal and mechanical properties of composite materials, and the application of composite PCMs in the thermal management of batteries are generally studied[107–110]. A novel thermal management strategy is proposed to enhance the mechanical molding property and prevent paraffin leakage to some extent[88]. The BTMS based on the composite materials of swollen graphite and paraffin and polyethylene configured with low fins has the high surface heat transfer capability. Additionally, the composite PCM indicated much better mechanical properties and cooling effect in comparison to swollen graphite and paraffin composition and air cooling. At the discharge rate of 3.5C, the as-constructed battery pack based on composite PCM effectively keep battery temperature within 50℃ and temperature difference of 5℃ for LiBs. However, PCM can only absorb heat passively. Under extreme conditions, such as high ambient temperature and high heat flux, the depletion rate of effective phase change enthalpy is speedy. Once it is exhausted, the thermal management system may fail. The hybrid cooling methods based on PCM combined with other cooing strategy, such as liquid cooling and HP system, can effectively alleviate the above issues. Research constructed the water-based N-eicosane particles (130nm) emulsion flow in two multi-channel heat sinks with eight parallel and divergent rectangular mini-channels. Therein, the channel was installed at an angle of 2.06°. It is found that compared with pure water, nano-PCM emulsion can obviously increase the heat transfer performance of heat sink. With $Re_{bf} = 295$ (i.e., Reynolds number of base liquid) and pump power is 3.21 W/cm^2, the heat transfer enhancement is up to 13.8% in the divergent mini-channel heat sink[111]. Additionally, the PCM (N-eicosan) was added in the mini-channel cold plate as hybrid mini-channel cold plate that has also improved the heat transfer rate, under the heat generation rate is 400 kW/m^3 and the water inlet is 0.01 m/s with 298.15 K temperature, by comparing the mini-channel cold plate whether contains PCM to analyzed the cooling performance. The results shown that the temporal average of the maximum battery temperature in hybrid cooling system are 0.06, 1, and 10.35K lower in comparison to mini-channel cold plate cooling in Q = 100, 200, and 400 kW/m^3, respectively[112]. In terms of hybrid thermal management optimized method, [79] applied the Kriging-High dimensional model representation (HDMR) method to establish a surrogate model of the hybrid BTMS. Therein, the hybrid BTMS based on PCM, liquid cooling and HP is researched. Moreover, the main sensitive factors and temperature difference of battery are determined by global sensitivity analysis. And the multi-objective particle swarm optimization is adopted as the optimization strategy for thermal management system. Under the 5C discharging-1C charging process and TR conditions, the optimized hybrid BTMS has the best heat dissipation characteristic with a highest cell temperature of 30°C and the lowest temperature difference (2.31°C). The optimized results shown that the surrogate model based on Adaptive-Kriging-HDMR strategy can guarantee high calculation accuracy and decline the hybrid BTMS of calculation cost. In conclusion, through PCM combining other cooling strategy can effectively alleviate the low latent heat issues of PCM.

The HP is a kind of high-performance thermal transfer element based on gas-liquid phase change. It uses the evaporation and condensation of refrigerant to transfer heat. It has high directional thermal conductivity, and its thermal conductivity is higher than any known metals. As a result, it has been widely used in many industrial fields[113]. Gan et al. proposed an equivalent thermal resistance model for the BTMS of HP[114]. Liang proposed a battery module thermal management system using HP and discussed its thermal performance and electrochemical performance through experiments and models. The research results indicated that HP has a good application prospect for battery cooling[115]. The HP also can couple with other kinds of cooling systems such as PCM. As reported in literature[116], the as-constructed HP-assisted PCM based battery thermal management is feasible and effective with a relatively longer operation time and more suitable temperature. Compared with PCM based modules, the HP-assisted PCM battery module operates longer when it reaches the set temperature of 50°C.Additionally, a sandwich structure consisting of a battery, PCM, and HP was proposed by Jiang. The lumped thermal model considered the PCMs melting and the thermal response of the HPs, and revealed the underlying coupling mechanism of battery temperature and phase change process at different environment temperatures, different heat transfer coefficients at condensation section, and different thickness ratios of PCM and battery[117].

The refrigerant direct cooling system is a novel BTMS, which also uses gas-liquid phase change to transfer heat[118–120]. This system can combine the air conditioning system with the battery cooling system. It dramatically reduces the complexity of the secondary liquid heat exchange cooling system with multiple branches[26]. In the direct cooling thermal management system, the evaporator cold plate directly installs in the battery module. The refrigeration cycle is realized by connecting the refrigerant circuit with the existing air conditioning system. The evaporator cold plate and the air conditioner evaporator are in two different positions in parallel refrigeration cycles[121]. As shown in Fig. 5, Shen et al. propose a new synergistic control of a direct cooling system with an on-board air conditioning system to enhance the performance of battery thermal management. In particular, the system's thermal response, energy efficiency, and irreversibility are analyzed based on the vehicle system framework for high ambient temperature and high speed dynamic conditions. A mathematical simulation model of the refrigerant-based BTMS was developed and analyzed its performance under different pressure conditions based on AMESim. Under high temperature and high speed conditions, this direct cooling system can effectively reduce the temperature rise of the cells (≈25°C) due to the large amount of latent heat that accompanies the phase change process. The temperature uniformity between the cells can also be well ensured (≈ 3°C)[122]. However, since one refrigerant loop is connected to two evaporators simultaneously, the different heat load requirements of the passenger compartment and the battery system may lead to contradictions in thermal control strategies. If there is a conflict between these two requirements, the thermal comforts of passengers may be affected because for safety reasons, the priority of using refrigerant is given to the BTMS[123]. Therefore, a multi-objective cooperative thermal control strategy is fundamental to balance the thermal demands of batteries and passengers. In addition, since the compressor must continuously operate regardless of the cabin air conditioning, the system may have a high power consumption.

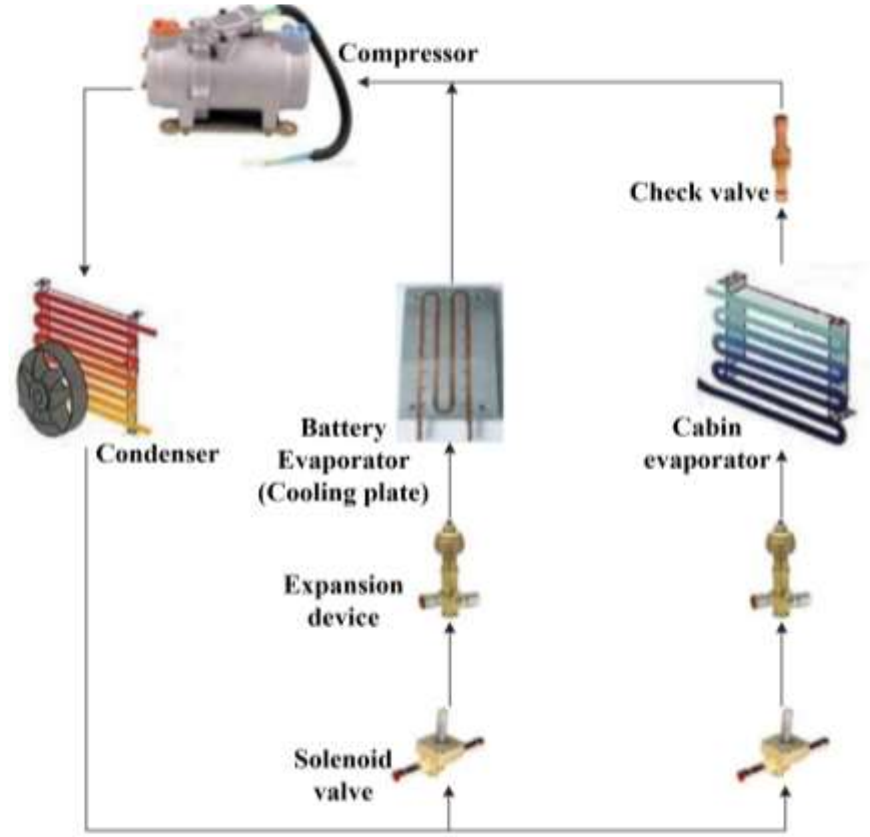

FIGURE 5 Diagram of the coupling thermal management system[122]

3.1.4. Thermoelectric element cooling system

The cooling system of the thermoelectric elements have been widely studied for its clean energy and environmentally friendly management[124]. Thermoelectric generators (TEG) can convert heat into electrical energy, and the excess heat can convert to power other devices. The thermoelectric cooler (TEC) can convert electrical energy into heat energy to provide heating and cooling for various electrical equipment. In recent years, automobiles have already used the TEC for auxiliary functions. For example, the temperature control in the cabin of EVs and the heating and cooling seats in a luxury car is also suitable for BTMS[125]. TEC consists of P-type and N-type semiconductors matrix. This component uses current to pass through a circuit composed of the TEC matrix to generate heat between the two semiconductors by the Peltier effect [126]. Liu et al. indicated a novel BTMS that combing TEC with liquid cooling and established a thermal model of a battery, and a TEC and calibrated the model with experimental data[127]. Troler et al. researched the effect of artificially induced temperature gradients on cell performance by using TEC to maintain the temperature gradient of the LiBs under isothermal and non-isothermal conditions[128]. The thermoelectric thermal management system can accurately control the temperature. However, it consumes a large amount of energy due to its low efficiency.

Table 3

The battery thermal management technology comparison

reference	Cooling methods	subject	Merit	Demerit
Chen and Song.[24] in 2019	Air-cooling	Optimizing cell spacing of pack in the parallel air-cooled	The optimal system performs good for various inlet airflow rates, high stability.	The experimental conditions are relatively single, and many variable factors need to be determined.
Chen et al. [25] in 2019	Air-cooling	The influence of inlet region and outlet region for cooling performance	The experimental is easy to implement and the model has high accuracy.	There are few comparative experiments, more schemes should be adopted for comparison.
Shang et al. [19] in 2019	Liquid cooling	Thermal management system based on liquid cooling	Low computational cost, BTMS has the high reliability.	The influence of many physical properties of coolant on the system needs to be further studied.
Kiani et al. [98] in 2020	Nanofluids liquid-cooling	Application of nanofluids in liquid cooling	The comparative experiment is representative and reliable	The effect of nanoparticle diameter on the experimental results was not considered in this experiment.
Heyhat et al. [108] in 2020	PCM cooling	Composite PCM use in battery thermal management	High model accuracy, the experimental and simulation results has the excellent fitting	The effect of distribution of nanoparticles in composite PCM on cooling performance needs to be further studied

Zhang et al. [80] in 2021	Hybrid cooling	Application of surrogate model in hybrid BTMS	High calculation accuracy, low calculation cost	The experiment only studied the cooling effect of a single battery
Liao et al.[129] in 2021	Thermoelectric element cooling	BTMS used TECs	Strong adaptability, wide operating temperature range.	Complex structure, lack of experimental verification
Lyu et al.[130] in 2019	Thermoelectric element cooling	TECs are used for thermal control in LiBs	Rapid and accurate cooling strategy	There are many interference factors in the experimental content, and the experimental has limitations.

3.2 Preheating works at low temperature

The performance of the LiBs will significantly reduce at low temperatures. Hence it is necessary to preheat the LiBs in EVs at low temperatures. Generally, preheating methods included external heating and internal heating, as presented in Fig. 6. The external heating system is usually the most common and simplest method[131,132] but requires the radiation heater and is complex in structure. Internal heating system can reach the predetermined temperature quickly, but the safety risk is high[133].

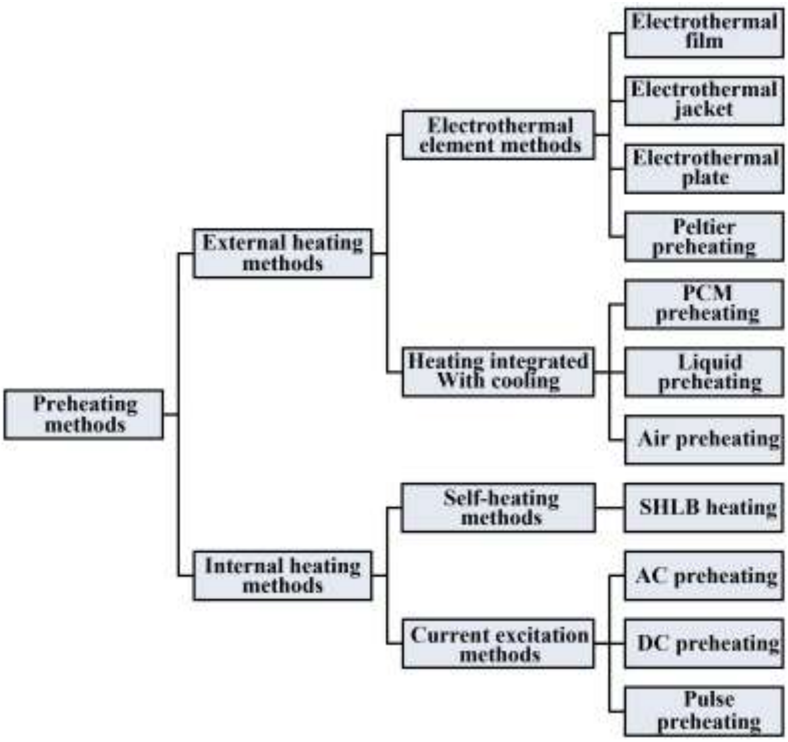

FIGURE 6 Classifications of battery preheating methods [134]

3.2.1 External heating

For all types of batteries, air preheating is a suitable method and has been widely used in EVs [135–137]. However, the air circulation requires the configuration of the fan and flow channels, which will increase the complexity and reliability issues of the BTMS. The noise produced by the fans could cause the poor comfort of the driver and passengers to a certain extent. Moreover, because of the low thermal conductivity of air, whether it is passive or active air heating, this will extend the working time for preheating the battery.

The liquid preheating system has an ideal preheating effect due to its higher thermal conductivity and heat transfer rate, but the preheating system as a whole is relatively complicated[138]. Most of the liquid preheating system includes heaters and heat exchangers, among which the cell contacts the heat exchanger, and it preheats the cell by flowing liquid through the heat exchanger. As shown in Fig. 7, under New European Driving Cycle conditions, Wu et al. implemented a method for externally preheating cells with liquid. The experimental battery pack could be heated from -30°C to 10°C within one hour and the maximum temperature difference between the cell could be reduced to 1.6°C[139]. According to the contact type between the liquid medium and the battery, liquid preheating BTMS could be classified as non-contacting preheating and immersing preheating[140]. The non-contacting liquid preheating method has been applied to EVs. For example, Volt heats the liquid medium using electric heaters, which flows into the whole battery pack[141,142]. In addition, Tesla Motor also uses the liquid heating method to heat the battery pack. The flow circuit used in the system included four channels that allow the liquid medium to flow more fully and shorten the preheating time[143, 144]. In general, the immersing preheating has a higher thermal conductivity than the non-contacting preheating, so the battery has a more uniform temperature distribution during the heating process. Nevertheless, effectively preventing the leakage of the liquid medium is still a significant issue, and the liquid medium is required to have good electrical insulation properties to reduce the risk of the short circuits [134].

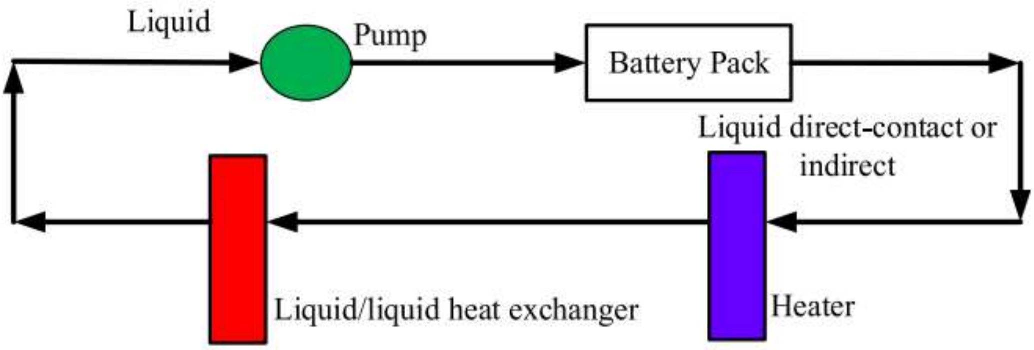

FIGURE 7 The schematic of liquid-based BTMS[139]

Compare with air and liquid, PCMs can absorb and release heat from the external environment during phase transitions. The melting process can apply to equipment cooling, and the solidification process can be used for low temperature heating[145]. The PCM is generally isolated from the battery by the container. The advantage of PCM-based BTMS is that it can keep the temperature uniformity of the battery. Hence it is beneficial to prolong the lifespan of the batteries. Rao et al. conducted a comparative simulation for PCM and air preheated batteries, and the results of the present study indicated that as the thermal conductivity of the PCM increases, the temperature difference decreases. The heating time of air-heating was 6.4, 5.2, and 4.2 times of that of PCM-heating when the battery was heated from -30°C, -20°C, and -10°C to 10°C, with the initial temperature of air and PCM being both 50°C [146]. As shown in Fig. 8, a battery preheating scheme for paraffin/graphite composite PCM was proposed by Zhong et al. The cell in each module is wrapped with parallel resistive wires, and then the remaining space within each module is filled with composite PCM. Five resistance wires can heat the battery from -25°C to 10°C in 273 seconds, consuming 2948 J of energy[147].

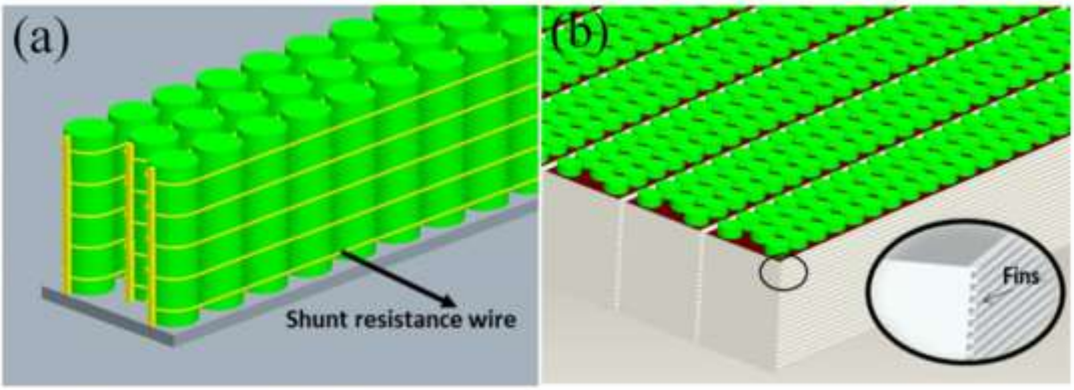

FIGURE 8 PCM-based preheating system for batteries[147]. (a) The battery module with resistance wire twined around battery cells. (b) The battery pack consists of battery modules with CPCM perfused in each module.

Besides, the preheating of the battery can be realized by electrothermal elements, which include electrothermal films and electrothermal plates[148]. From the related research, the electrothermal films can keep a better temperature distribution during the heating process because of its performance, which is more suitable for the preheating work of the battery pack and can effectively avoid the inconsistent temperature distribution of the LiBs during the heating process[149]. Yet, whether this method impacts LiB life remains to be studied[135].

3.2.2 Internal heating

In general, the internal preheating methods of the battery include self-heating and current excitation heating. Compared with the external heating method, the internal heating method has higher heating efficiency, and no requirements for cell shape[149]. However, the heat generation mechanism is very complex, and improper use may cause safety problems. As shown in Fig. 9, Wang et al. have developed a self-heating LiB that could self-heat in low temperature ambient environment. The cell is heated by inserting a nickel foil with two tabs into the LiB to generate heat. More notably, during the activation process, the surface temperature of the battery rises rapidly from -20°C to 0°C in a matter of seconds[150,151]. Self-heating is an efficient strategy for preheating LiBs. But the self-heating effect of LiBs is limited by the physical properties of the cell. In addition, most experimental data are only obtained from single battery. For a battery pack with hundreds of individual cells, this cell modification could be prohibitively expensive. Further, because the internal structure of the cell is changed, it cannot use in current EVs due to safety concerns. The safety issues of the self-heating method still need further study.

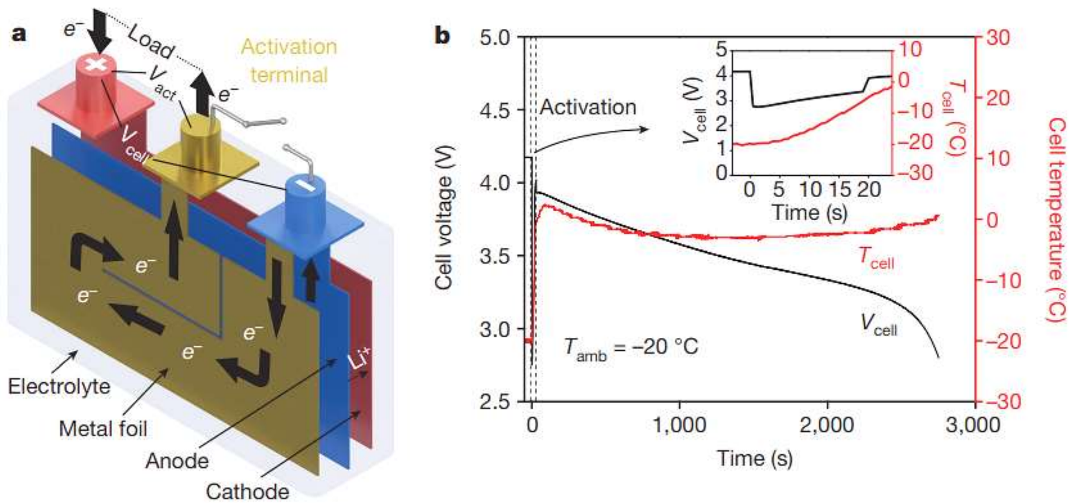

FIGURE 9 (a) The schematic of self-heating battery. (b) Cell voltage and temperature evolutions during Vact=0.4V (inset) and subsequent 1C discharge at -20°C[151].

Current excitation can be direct current (DC) preheating, alternating current (AC) preheating, or pulse preheating. Heating the battery by discharging the battery at a certain constant current is called DC preheating, which releases the energy stored inside the battery. To avoid lithium plating and battery aging during preheating, it is necessary to control the current amplitude and preheating time within a certain limit[152,153]. By increasing the discharge rate and lowering the cut-off voltage of DC preheating, i.e., prolonging the discharging time, the heating rate can be increased[154].

AC preheating method applies AC current of a specific frequency and amplitude to the cathode and anode of the cell, and the heat is generated from the internal impedance[155,156]. Compared with the DC preheating method, the AC preheating method can more quickly and more effectively heat the battery [157]. Zhang et al.

adopted a lumped energy conservation model to predict the battery temperature under AC preheating. They preheated the battery with a sinusoidal AC at different frequencies and current at low temperature. The results showed that the preheating time decreased with the increase of the AC amplitude and the decrease of the frequency. Better thermal insulation of the battery also helped to reduce the preheating time[158]. It should be noted that the AC heating effect will reduce with the constant amplitude, when the frequency is too low. However, this study did not show how to optimize the AC amplitude and frequency to improve the heating rate. Besides, the impact of the applied AC current on battery health is still unclear. In addition, the AC preheating method requires an external power supply, which increases the cost or limits the application scenarios and may be the reason why it hasn't been used commercially[135,147].

Pulse preheating method uses pulse current to generate heat through the internal impedance of the cell to preheat the batteries. Compared with air preheating, the pulse preheating method can achieve a more uniform distribution of heat generation inside the battery pack, and a low temperature variance is beneficial to battery health [159]. An effective preheating strategy is developed by using a thermo-electric coupling model based on the EIS of the cell and the pulse frequency is varied between 1000Hz and 3637.1Hz to compare their preheating effect. The optimal pulse configuration (the 2637.5Hz frequency) can heat the cell from -20℃ to 5℃ within 1000 seconds. The battery's performance temperature is significantly improved after this temperature rise. Further, experimental data show that the damage to the battery health, in terms of capacity attenuation and internal impedance rise, is minor[160]. However, this method is only validated in the laboratory, and its effectiveness has not been verified in the actual vehicle.

3.3 Thermal runaway treatment

The mechanical, electrical, and thermal abuses (overcharge, over-temperature and metal penetration, etc.) of LiBs can cause the TR phenomenon, which will pose a safety hazard to the battery pack and passengers[158]. Battery TR, if not detected and interrupted in time, will cause serious safety accidents [26]. At the same time, due to the large specific heat of the battery system, it is difficult to quickly control the temperature to reach the predetermined temperature range when the TR occurred, so there is a lag problem in the thermal management system. For these issues, there are four categories of emergency battery thermal barrier (EBTB), including material optimization, the TR forewarning strategy, fire extinguishment, and heat removal.

Material optimization strategies include Electrolyte additives, separator safe and electrode design. Wang et al. proposed a new idea to enhance the battery safety by passivating the cell first and then self-heating before use. They had proved that, adding triallyl phosphate to the electrolyte, can improve the stability of LiB under high pressure and high temperature operating conditions[161,162]. Liu et al. demonstrated a new type of separator that improves flame retardancy by adding triphenyl phosphate to the conventional electrolytes. During LiBs TR, the protective polymer shell would melt, releasing the flame retardant to suppress the burning of the electrolyte inside the battery[163]. Chen et al. proposed a thermoresponsive polymer switch material, a mixture of graphene-coated sharp nickel nanoparticles. Once the TR phenomenon occurs and the battery temperature rises above switching temperature (T_s), the conductivity of this material will drop sharply, thereby suppressing further exothermic side reactions and the propagation of TR[30,163].

Emergency cooling system needs to monitor the battery temperature and detect the starting point of TR and then quickly remove the accumulated heat. The pre-warning of TR depends on the early detection of abnormalities in the measurements of the battery's terminal voltage[164], mechanical deformation[165], internal temperature[166], and internal impedance of the battery[167]. Additionally, the gas component identification is another useful method for thermal runaway prewarning[77]. Zhu et al. indicated that the voltage of LiBs would drop sharply before TR occurs, and this characteristic can be used to warn the upcoming risk of TR[168]. After a TR warning , the battery pack must initiate the heat-dissipation procedure immediately [169]. Once the TR or even an explosion hazard happens, firefighting and heat removal must be carried out to cut the propagation routes and to control the damage. Wang et al. studied using dry powder and water to extinguish the flame, and showed that this measure can suppress the TR propagation of LiBs[170–172]. As shown in Fig. 10, Liu et al. proposed a novel BTMS with combining fast water mist and $C_6F_{12}O$ cooling. They found out that this method could reduce significantly the peak temperature and the high-temperature duration of the cell after TR, as compared to the method with $C_6F_{12}O$ only and without suppression during the heatwave. After the TR is initiated, by combining the $C_6F_{12}O$ and the water mist to spray onto the battery surface, the cell can be effectively cooled [173]. Additionally, an optimized dual-functional battery module that involved PCM and aerogel is indicated[174]. The PCM inset EG availably suppress the combustion flame and reclined the peak temperature of battery. Meanwhile the aerogel showed the outstanding performance in delaying battery TR. The proposed BTMS combined the advantages of aerogel and PCM. The optimized module delays the initial time of TR by 173s and alleviates the thermal propagation. Moreover, reducing the maximum temperature of battery module to 29℃. Meanwhile, studies have shown that emergency spray flow has the limited efficiency on reducing the temperature of TR battery, wherein the nozzle initial condition is set to 0.2Mpa, 0.5L/min^{-1} and the spray angel is about 60°. The fact is that spray cooling can be adopted to the emergency cooling strategy to suppress TR[175]. In addition to mentioned methods, Gao et al. investigated in depth the emergency cooling and overheating control of LiBs, and together with the direct cooling BTMS. They proposed an open-loop emergency safety control method, namely, when the TR state is detected, refrigerant is directly injected in the LiBs pack for emergency cooling and flame retardancy[176].

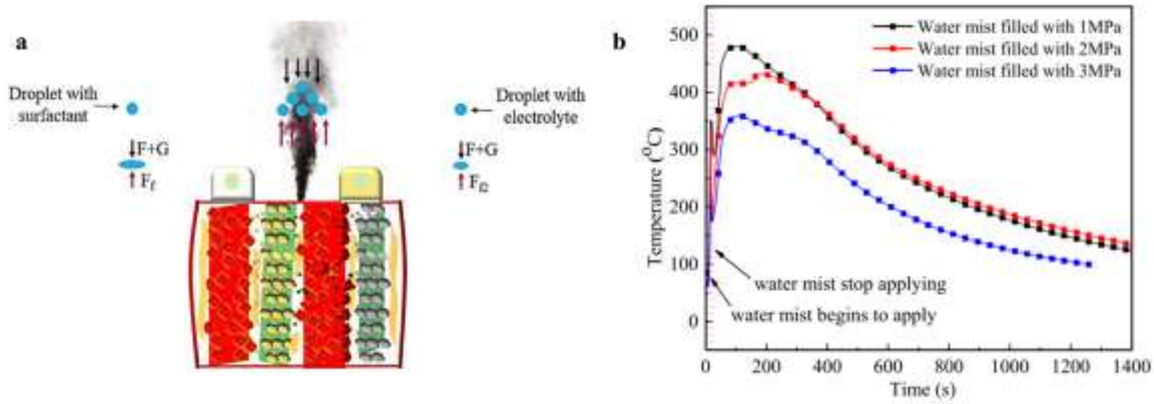

FIGURE 10 (a) Schematic diagram of water mist penetrating plume. (b) Temperature response for long surface of experiments extinguished and cooled by water mist with various working pressure[173].

In addition to the study of experimental mechanisms for triggering thermal runaway, model-based TR predictions are essential for optimizing the safety design of batteries. Jin et al. used COMSOL software to build a three-dimensional lithium-ion battery model to investigate the combined effect of heating power and heating area on triggering thermal runaway. The experiment adopted eight heating strategies, i.e., a combination of two different heating powers and four incremental heating areas. The results show that the area with a lower heating power density can trigger thermal runaway faster with the same heating method. Based on the simulation results, recommended strategies for thermal runaway prediction and low-temperature heating solutions are proposed[177]. Ren et al. proposed a novel model for predicting thermal runaway in lithium-ion batteries. Differential scanning calorimetry (DSC) tests on individual cell components, and their mixtures were used to reveal and characterize the thermal runaway mechanism. Six main reactions (e.g., decomposition of the solid electrolyte interfacial film) are used as the main heat generation sources. The kinetic parameters of each exothermic reaction are determined using the Kissinger method and a non-linear fitting approach. The model is in good experimental agreement with the results of adiabatic TR tests and oven experiments for 24Ah Li-ion batteries. The results show that the model can respond well to the thermal runaway mechanism of the battery[178]. Sara Abada et al. developed a three-dimensional physical model of the electrothermal behavior of lithium-ion batteries under thermal runaway conditions. The combination of experimental and modeling analysis enables an excellent understanding of the mechanisms of thermal runaway in Li-ion batteries and the implications for battery aging. The experiment found that calendar aging leads to a delay in the self-heating temperature of the battery so that thermal runaway can be triggered at lower temperatures. Meanwhile, the experimental results are in good agreement with the simulation model [179].

4. Connection and development of thermal management system and CHAIN

Due to the large specific heat of the battery system, it is difficult to quickly control the temperature to reach the predetermined temperature range, namely, the thermal management system exists lag problem. In addition, due to different triggering reasons and the complexity of battery aging and environmental impact, pre-warning of TR is a critical challenge[180]. Through the early prediction and pre-warning can alleviate above issues. Combining BTMS with cloud computing to improve the computational power and data storage capacity can enhance the response speed and TR early warning ability. With the Internet of things (IoT), all battery relevant data can be measured and transmitted to the cloud seamlessly, building up a digital twin for the battery system. Diagnostic algorithms evaluate the data and enable optimization of the battery charging, aging, and thermal management[181]. The CHAIN framework was proposed by Yang et al. It is suggested that the critical physical and electrochemical parameters of battery from production to use should be uploaded to the cloud server to optimize the whole life management of the battery system. From the above-mentioned issues, a novel solution for battery thermal management is proposed, which combines traditional BTMSs with the CHAIN architecture through the “end-edge-cloud” multi-layer collaborative lay-out to achieve cloud-enhanced BTMS[182]. As shown in Fig.11, CHAIN integrates the cyber-end and the vehicle-end, which can generate additional functionality by adding new complex layers. Meanwhile, it may lead to potentially complicating the design to guarantee performance on the cyber-end, while the single vehicle-end carries out recording and uploading real-time data and executing commands from the cyber-end via wireless communication[183]. In addition, Wu et al. pointed out that a digital twin model of battery could be created, combining the knowledge of battery degradation, modeling tools, and diagnosis with machine learning. This network, through establishing the mapping relationship between the physical and digital embodiment of the battery, can achieve a more intelligent control and a longer service life[184].

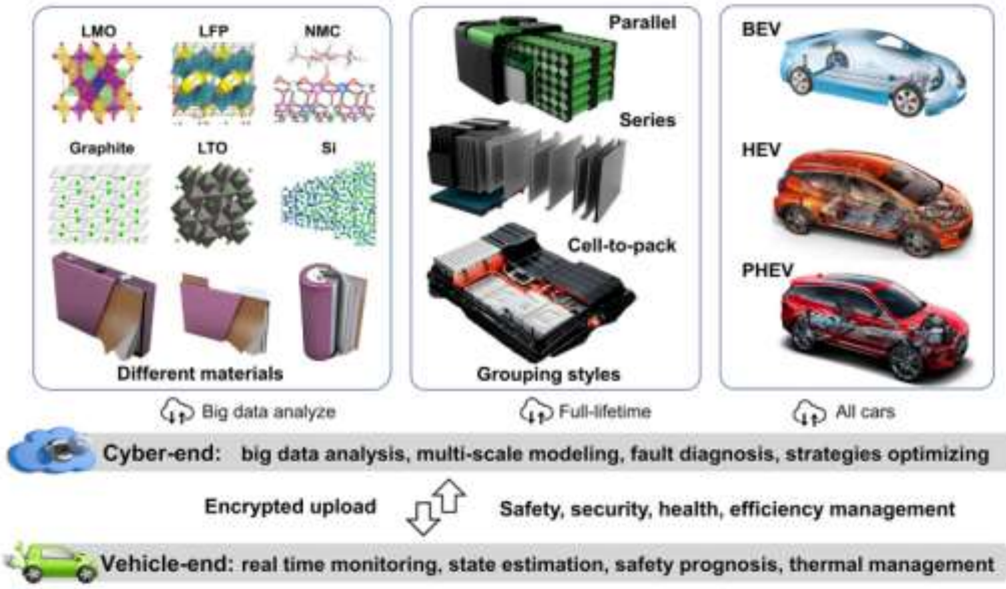

FIGURE 11 Multi-condition Control and Multi-Lifespan Recurrence[183]

Based on the points mentioned above, this paper presents a novel digital solution for BTMS, as depicted in Fig. 12. The digital twin of battery is established to realize the mapping of physical and digital entities. Some the basic data of battery are collected at the vehicle end, mainly including current, temperature, acoustics, gas and battery or module deformation. The data is transmitted to the cloud based digital twin through IoT technology, where data is collected and processed. The cloud based digital twin feeds back the corresponding control parameters to the vehicle end, so as to realize accurate and efficient battery thermal management. Some basic functions and data are executed and processed locally at the vehicle end, so as to reduce the computing load capacity of the cloud. The local model and algorithm processing are used to data driven of the vehicle end BTMS. Finally, based on the mirrored function of the digital twin framework, it can realize the functions of diagnosis and early warning, state estimation and data processing, it better serves the cloud based digital twin and the local computing at the vehicle end. The proposed digital solution described in this paper mainly includes the following parts: on-board sensing, local computing and cloud based digital twin.

4.1 On-board sensing

The condition for the current intelligent BTMS is to accurately collect the relevant data of the system and infer the state of the system from these data. The data acquisition depends on the sensing ability of the local terminal hardware. The information collected by the battery system is as described above, such as current, voltage, temperature, acoustics and deformation. Advanced IoT devices can provide stable and fast computing, transmission and connection capabilities to effectively transmit data. Therefore, it is very important to develop advanced sensor technology to sense the current state of the battery. As described in literature[185], mist computing can process data at the extreme edge of the network, which can be realized separately on the current Internet of things devices without communicating with the local computing or cloud, so as to reduce the communication demand.

4.2 Local-computing based on vehicle end

In specific cases, the ability of monitoring and processing information of the BTMS is very demanding on time. When the transmission communication and cloud computing capacity of the Internet of things are limited, edge computing is an effective way to reduce the efficiency of cloud load computing. Therefore, several thermal management functions be finished on vehicle-end, such as the efficient preheating, rapid cooling and TR treatment. In addition, there are also including the electro-chemical model and thermal model computing. For improving the reliability of the thermal management system, the functions of each point during operation should be operated locally. Then the functions of data transmission, data synchronization and local computing are realized in the edge computing[186].

4.3 The cloud based digital twin

with the amount of data generated, data aggregation, machine learning and hybrid intelligent learning and control key algorithms be achieved in the cloud-end, which the functions included data driven optimal, prognostics and digital health metrics. Utilizing cloud computing and storage capabilities to conduct aggregation analysis and feature extraction for the data in the cloud-end. Meanwhile, machine learning, artificial neural network and other algorithms are used to predict the battery health state and heat generation, and conduct the fusion model for the battery mechanism model and equivalent circuit model. The model algorithm is used to fuse historical health data to provide pre-warning work of TR.

In addition, based on the CHAIN and digital twin framework, IoT and 5G technology to realize the multi-scale and multi-stage prognostics and thermal management. Finally, the mirrored system runs the advanced thermal model, diagnosis and control algorithms to predict and evaluate the battery's SOX and internal temperature. Meanwhile, it can also optimize the operating parameters, such as the charging rate. These battery control parameters are then transmitted to the vehicle end. With the greatly expanded computational capacity enabled by the cloud, advanced battery management algorithms, such as data-driven and machine learning fleet management tools[186] can be implemented.

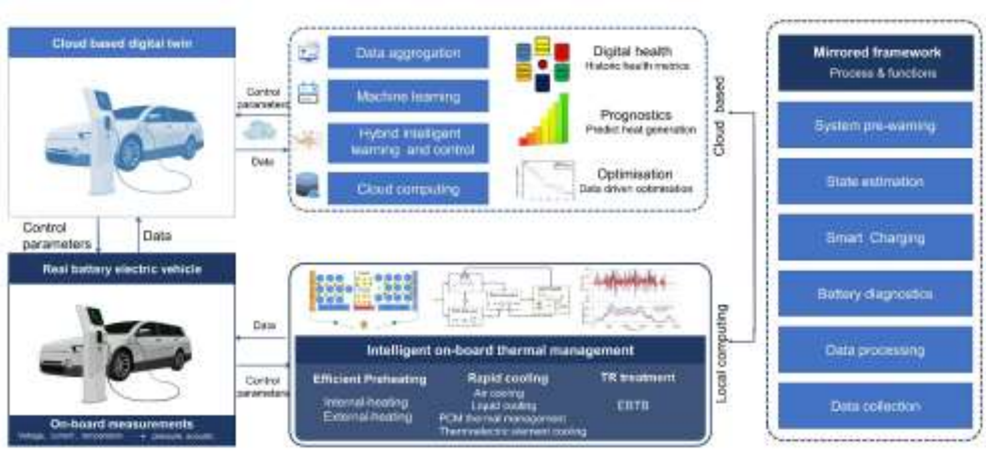

FIGURE 12 Battery thermal management system leveraging from CHAIN [31,45,89,122,187,188]

5. Conclusion and future task

5.1 Work summary

This paper provides a comprehensive review of the heat generation mechanism and thermal models of LIBs, along with the existing battery thermal management strategies. A comprehensive discussion of the heat generation mechanism and heat transfer models of batteries is presented, enabling an understanding of the approach and importance of battery thermal management. Then, this is followed by introducing current battery thermal management strategies, namely air cooling, liquid cooling, phase change materials, and electronic component cooling. Several comprehensive analyses of the various thermal management strategies are investigated from model to experiment. Finally, the paper proposes a CHAIN-based battery thermal management system, which is explained in detail from three aspects: vehicle-side sensing, edge computing, and cloud-based digital twin. Finally, the paper aims to enable researchers to understand the current thermal management strategy trend.

5.2 Prospects

In terms of existing BTMS status, it has some simple functions such as open-loop control, limited use of model/diagnosis/prediction capacity etc., additionally, no intelligence or predictive control and difficulty of maintenance/repair. With the continuous development of communication technology, the future BTMSs have the smart battery pack with embedded sensors, new efficiency thermal management approaches and telematics system 5G etc. Intelligent BTMS enabled by cloud-computing can fused big data, advanced diagnosis and optimization algorithms. Such as digital twin and machine learning, optimal/predictive maintenance and repair, data-driven fleet management can be implemented in the smart BTMS. Furthermore，BTMS will not only ensure the battery keeps more safe, efficient, and reliable conditions, but communicate and collaborate in other fields, such as microgrid. The future task followed as by:

1) Developing advanced sensing technology, such as fiber-optic sensing, sensor based piezoelectric/pyroelectric poly and a thin-film transistor array and wireless sensor.

2) Fusing the advanced data model algorithm by linking the historical data and real-time data to feedback, modifying the thermal model to provide a more accurate heat generation prediction.

3) Predicting and pre-warning technology of battery heat generation and TR combined with CHAIN and digital twin to avoid TR events.

Declaration of Competing Interest

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.

Acknowledgment

This work is supported by the National Natural Science Foundation of China under the No. U1864213.

Reference

[1] L. Ghadbeigi, B. Day, K. Lundgren, et al. Cold temperature performance of phase change material based battery thermal management systems. Energy Reports, 2018, 4:303–307.

[2] J.P. Robinson, J.J. Ruppert, H. Dong, et al. Sintered electrode full cells for high energy density lithium-ion batteries. Journal of Applied Electrochemistry, 2018, 48:1297–1304.

[3] X. Han, X. Feng, M. Ouyang, et al. A Comparative Study of Charging Voltage Curve Analysis and State of Health Estimation of Lithium-ion Batteries in Electric Vehicle. Automotive Innovation, 2019, 2:263–275.

[4] K.C. Pu, X. Zhang, X.L. Qu, et al. Recently developed strategies to restrain dendrite growth of Li metal anodes for rechargeable batteries. Rare Metals, 2020, 39:616–635.

[5] S. Ma, M. Jiang, P. Tao, et al. Temperature effect and thermal impact in lithium-ion batteries: A review. Progress in Natural Science: Materials International, 2018, 28:653–666.

[6] W. Zhuang, Z. Liu, H. Su, et al. An intelligent thermal management system for optimized lithium-ion battery pack. Applied Thermal Engineering, 2021, 189: 116767.

[7] M. Akbarzadeh, J. Jaguemont, T. Kalogiannis, et al. A novel liquid cooling plate concept for thermal management of lithium-ion batteries in electric vehicles. Energy Conversion and Management, 2021, 231: 113862.

[8] P.R. Tete, M.M. Gupta, S.S. Joshi. Developments in battery thermal management systems for electric vehicles: A technical review. Journal of Energy Storage, 2021, 35:102255.

[9] W. Z. Chen, D. C. Qing. A comprehensive review on thermal management systems for power lithium-ion batteries. Renewable and Sustainable Energy Reviews, 2021, 139: 110685.

[10] M. Luo, J. Song, Z. Ling, et al. Phase Change Material (PCM) coat for battery thermal management with integrated rapid heating and cooling functions from -40 °C to 50 °C. Materials Today Energy, 2021, 20:100652.

[111] Y. Liu, S. Wang. The effect of high temperature on the loss rate of capacity of lithium-ion battery. ResearchGate,2020, 12:360921.

[12] K. Chen, M. Song, W. Wei, et al. Design of the structure of battery pack in parallel air-cooled battery thermal management system for cooling efficiency improvement. International Journal of Heat and Mass Transfer, 2019, 132:309–321.

[13] K. Chen, W. Wu, F. Yuan, et al. Cooling efficiency improvement of air-cooled battery thermal management system through designing the flow pattern. Energy, 2019, 167:781–790.

[14] Z. Shang, H. Qi, X. Liu, et al. Structural optimization of lithium-ion battery for improving

thermal performance based on a liquid cooling system. International Journal of Heat and Mass Transfer, 2019, 130:33–41.

[15] R. Fraser. Coupled Electrochemical-Thermal Simulations and Validation of Mini-channel Cold-Plate Water-Cooled Prismatic 20 Ah LiFePO4 Battery. Electrochem, 2021, 2:643-663.

[16] S.D. Chitta, C. Akkaldevi, J. Jaidi, et al. Comparison of lumped and 1D electrochemical models for prismatic 20Ah LiFePO4 battery sandwiched between mini-channel cold-plates. Applied Thermal Engineering, 2021, 199:117586.

[17] S. Wiriyasart, C. Hommalee, S. Sirikasemsuk, et al, Thermal management system with nanofluids for electric vehicle battery cooling modules. Case Studies in Thermal Engineering, 2020, 18:100583.

[18] L. Song. Thermal Performance Analysis of the Battery Thermal Management Using Phase Change Material. Open Access Library Journal, 2018, 05:1–5.

[19] H.-P. Li, X.-Y. Ji, J.-J. Liang. Dual-functional ion redistributor for dendrite-free lithium metal anodes. Rare Metals, 2020, 39: 861–862.

[20] A. Vgc, A. Asd, B. Sp, et al. Numerical investigation on thermal behaviour of 5×5 cell configured battery pack using phase change material and fin structure layout. Journal of Energy Storage, 2021, 43:103234.

[21] J. Qu, Z. Ke, A. Zuo, et al. Experimental investigation on thermal performance of phase change material coupled with three-dimensional oscillating heat pipe (PCM/3D-OHP) for thermal management application. International Journal of Heat and Mass Transfer, 2019, 129:773–782.

[22] Q. Wang, Z. Rao, Y. Huo, et al. Thermal performance of phase change material/oscillating heat pipe-based battery thermal management system, International Journal of Thermal Sciences, 2016, 102:9–16.

[23] N. Javani, I. Dincer, G.F. Naterer, et al. Heat transfer and thermal management with PCMs in a Li-ion battery cell for electric vehicles. International Journal of Heat and Mass Transfer, 2014, 72:690–703.

[24] Y. Liu, S. Yang, B. Guo, et al. Numerical Analysis and Design of Thermal Management System for Lithium Ion Battery Pack Using Thermoelectric Coolers, Advances in Mechanical Engineering. 2015, 6:852712.

[25] Y. Cai, Y. Wang, D. Liu, et al. Thermoelectric Cooling Technology Applied in the Field of Electronic Devices: Updated Review on the Parametric Investigations and Model Developments. Applied Thermal Engineering, 2018, 148:238-255.

[26] Y. Wang, Q. Gao, G. Wang, et al. A review on research status and key technologies of battery thermal management and its enhanced safety. International Journal of Energy Research,

2018, 42:4008–4033.

[27] C. Shum. Soft Sensors for State of Charge, State of Energy, and Power Loss in Formula Student Electric Vehicle. Applied System Innovation, 2021, 4: 4040078.

[38] S. Ma, M.D. Jiang, P. Tao, et al. Temperature effect and thermal impact in lithium-ion batteries: A review. Progress in Natural Science Materials International, 2018, 28:653-666.

[29] P. Peng, Y. Sun, F. Jiang. Thermal analyses of LiCoO2 lithium-ion battery during oven tests. Heat and Mass Transfer, 2014, 50:1405–1416.

[30] J. Lin, X. Liu, S. Li. A review on recent progress, challenges and perspective of battery thermal management system. International Journal of Heat and Mass Transfer, 2021, 167: 120834.

[31] G. Jiang, L. Zhuang, Q. Hu, et al. An investigation of heat transfer and capacity fade in a prismatic Li-ion battery based on an electrochemical-thermal coupling model. Applied Thermal Engineering, 2020, 171:115080.

[32] W. Mei, Q. Duan, C. Zhao, et al. Three-dimensional layered electrochemical-thermal model for a lithium-ion pouch cell Part II. The effect of units number on the performance under adiabatic condition during the discharge. International Journal of Heat and Mass Transfer, 2020,148: 119082.

[33] M. Al-Zareer, I. Dincer, M.A. Rosen. Development and analysis of a new tube based cylindrical battery cooling system with liquid to vapor phase change. International Journal of Refrigeration, 2019, 108:163–173.

[34] M. Farag, H. Sweity, M. Fleckenstein. Combined electrochemical, heat generation, and thermal model for large prismatic lithium-ion batteries in real-time applications. Journal of Power Sources, 2017, 360:618–633.

[35] X. Cheng, N. Shi, Y. Li, et al. Engineering-Oriented Modeling for Thermal Behaviors of 18650 Li-ion Batteries, Energy Procedia, 2017, 105:4757–4762.

[36] G. Gwak, H. Ju. Multi-Scale and Multi-Dimensional Thermal Modeling of Lithium-Ion Batteries, Energies, 2019, 12:824-830.

[37] R.M.R.A. Shah, M. Al Qubeissi, A. McGordon, et al. Micro Gas Turbine Range Extender Performance Analysis Using Varying Intake Temperature. Automotive Innovation, 2020,3 :356–365.

[38] S. Abada, G. Marlair, A. Lecocq, et al. Safety focused modeling of lithium-ion batteries: A review. Journal of Power Sources, 2016, 306:178–192.

[39] M. Keyser, A. Pesaran, Q. Li, et al. Enabling fast charging – Battery thermal considerations. Journal of Power Sources, 2017, 367:228–236.

[40] W. Wu, S. Wang, W. Wu, et al. A critical review of battery thermal performance and liquid based battery thermal management. Energy Conversion and Management, 2019, 182:262–281.

[41] X. Peng, C. Ma, A. Garg, et al. Thermal performance investigation of an air-cooled lithium-ion battery pack considering the inconsistency of battery cells. Applied Thermal Engineering, 2019, 153:596–603.

[42] K. Smith, C. Wang. Power and thermal characterization of a lithium-ion battery pack for hybrid-electric vehicles. Journal of Power Sources, 2006, 160:662–673.

[43] C.H. Doh, Y.C. Ha, S. wook Eom. Entropy measurement of a large format lithium ion battery and its application to calculate heat generation. Electrochimica Acta, 2019, 309:382–391.

[44] K. Wang, F. Gao, Y. Zhu, et al. Internal resistance and heat generation of soft package Li4Ti5O12 battery during charge and discharge. Energy, 2018, 149:364–374.

[45] H. Giel, D. Henriques, G. Bourne, et al. Investigation of the heat generation of a commercial 2032 (LiCoO2) coin cell with a novel differential scanning battery calorimeter. Journal of Power Sources, 2018, 390:116–126.

[46] P. Huang, P. Ping, K. Li, et al. Experimental and modeling analysis of thermal runaway propagation over the large format energy storage battery module with Li4Ti5O12 anode. Applied Energy, 2016, 183:659–673.

[47] M. chin Pang, K. Yang, R. Brugge, et al. Interactions are important: Linking multi-physics mechanisms to the performance and degradation of solid-state batteries. Materials Today, 2021, 02:1-37.

[48] M. Doyle, J. Newman, A.S. Gozdz, et al. Comparison of Modeling Predictions with Experimental Data from Plastic Lithium Ion Cells. Journal of The Electrochemical Society, 2019, 143:1890–1903.

[49] Z. Xi, H.J. Yin, C.L, et al. A transfer function type of simplified electrochemical model with modified boundary conditions and Pade approximation for Li-ion battery: Part 1. lithium concentration estimation. Journal of Power Sources, 2017, 352:245-257.

[50] A. Lamorgese, R. Mauri, B. Tellini. Electrochemical-thermal P2D aging model of a LiCoO2/graphite cell: Capacity fade simulations. The Journal of Energy Storage, 2018, 20 :289–297.

[51] M. Farag, M. Fleckenstein, S. Habibi. Continuous piecewise-linear, reduced-order electrochemical model for lithium-ion batteries in real-time applications. Journal of Power Sources, 2017, 342: 351–362.

[52] C. von Lüders, J. Keil, M. Webersberger, et al. Modeling of lithium plating and lithium

stripping in lithium-ion batteries. Journal of Power Sources, 2019, 414:41–47.

[53] N. Javani, I. Dincer, G. F. Naterer, et al. Heat transfer and thermal management with PCMs in a Li-ion battery cell for electric vehicles. International Journal of Heat and Mass Transfer, 2014, 72:690-703.

[54] S. C. Yang, Y. Hua, D. Qiao, et al. A coupled electrochemical-thermal-mechanical degradation modelling approach for lifetime assessment of lithium-ion batteries. Electrochimica Acta, 2019, 326:134928.

[55] M.A. Rahman, S. Anwar, A. Izadian. Electrochemical model parameter identification of a lithium-ion battery using particle swarm optimization method. Journal of Power Sources, 2016, 307:86–97.

[56] Y. Xie, S. Shi, J. Tang, et al. Experimental and analytical study on heat generation characteristics of a lithium-ion power battery. International Journal of Heat and Mass Transfer, 2018, 122:884–894.

[57] R.D. Jilte, R. Kumar. Numerical investigation on cooling performance of Li-ion battery thermal management system at high galvanostatic discharge. Engineering Science and Technology, an International Journal, 2018, 21:957–969.

[58] J. Li, L. Wang, C. Lyu, et al. New method for parameter estimation of an electrochemical-thermal coupling model for LiCoO2 battery. Journal of Power Sources, 2016, 307:220–230.

[59] A. Lamorgese, R. Mauri, B. Tellini. Electrochemical-thermal P2D aging model of a LiCoO2/graphite cell: Capacity fade simulations. Journal of Energy Storage, 2018, 20:289–297.

[60] M. Casisi, P. Pinamonti, M. Reini. Optimal lay-out and operation of combined heat & power (CHP) distributed generation systems. Energy, 2009, 34:2175–2183.

[61] Y. Tang, L. Wu, W. Wei, et al. Study of the thermal properties during the cyclic process of lithium ion power batteries using the electrochemical-thermal coupling model. Applied Thermal Engineering, 2018, 137:11–22.

[62] Y. Ye, Y. Shi, N. Cai, et al. Electro-thermal modeling and experimental validation for lithium ion battery. Journal of Power Sources, 2012, 199 : 227–238.

[63] M. Chen, F. Bai, W. Song, et al. A multilayer electro-thermal model of pouch battery during normal discharge and internal short circuit process. Applied Thermal Engineering, 2017, 120:506–516.

[64] C. Zhang, S. Santhanagopalan, M.A. Sprague, et al. A representative-sandwich model for simultaneously coupled mechanical-electrical-thermal simulation of a lithium-ion cell under quasi-static indentation tests. Journal of Power Sources, 2015, 298:309–321.

[65] E. Gümüşsu, Ö. Ekici, M. Köksal. 3-D CFD modeling and experimental testing of thermal

behavior of a Li-Ion battery. Applied Thermal Engineering, 2017, 120:484–495.

[66] M. Zhang, J. Chen, H. Li, et al. Recent progress in Li-ion batteries with TiO 2 nanotube anodes grown by electrochemical anodization. Rare Metals, 2021, 40: 249-271.

[67] A. De Vita, A. Maheshwari, M. Destro, et al. Transient thermal analysis of a lithium-ion battery pack comparing different cooling solutions for automotive applications. Applied Energy, 2017, 206:101–112.

[68] A. Rajan, V. Vijayaraghavan, M.P.-L. Ooi, et al. A simulation-based probabilistic framework for lithium-ion battery modelling. Measurement, 2018, 115:87–94.

[69] L. Han, Z. Tong. A thermal resistance network model based on three-dimensional structure, Measurement. 2019, 133:439–443.

[70] E. Piotrowska, A. Chochowski. Representation of transient heat transfer as the equivalent thermal network (ETN). International Journal of Heat and Mass Transfer, 2013, 63:113–119.

[71] Q.-K. Wang, Y.-J. He, J.-N. Shen, et al. A unified modeling framework for lithium-ion batteries: An artificial neural network based thermal coupled equivalent circuit model approach. Energy, 2017, 138 : 118–132.

[72] M.-T. von Srbik, M. Marinescu, R.F. Martinez-Botas, et al. A physically meaningful equivalent circuit network model of a lithium-ion battery accounting for local electrochemical and thermal behaviour, variable double layer capacitance and degradation. Journal of Power Sources, 2016, 325:171–184.

[73] L. Ramotar, G.L. Rohrauer, R. Filion, et al. Experimental verification of a thermal equivalent circuit dynamic model on an extended range electric vehicle battery pack. Journal of Power Sources, 2017,343:383–394.

[74] X. Feng, M. Ouyang, X. Liu, et al. Thermal runaway mechanism of lithium ion battery for electric vehicles: A review. Energy Storage Materials, 2018, 10:246-267.

[75] Z. Liao, S. Zhang, K. Li, et al. A survey of methods for monitoring and detecting thermal runaway of lithium-ion batteries. Journal of Power Sources, 2019, 436:226879.

[76] P. Lyu, X. Liu, J. Qu, et al. Recent advances of thermal safety of lithium ion battery for energy storage. Energy Storage Materials, 2020, 31:195–220.

[77] X. Feng, D. Ren, X. He, et al. Mitigating Thermal Runaway of Lithium-Ion Batteries. Joule, 2020, 4:743–770.

[78] Z.Y. Jiang, Z.G. Qu, J.F. Zhang, et al. Rapid prediction method for thermal runaway propagation in battery pack based on lumped thermal resistance network and electric circuit analogy. Applied Energy, 2020, 268:115007.

[79] W. Zhang, Z. Liang, W. Wu, et al. Design and optimization of a hybrid battery thermal management system for electric vehicle based on surrogate model. International Journal of Heat and Mass Transfer, 2021, 174:121318.

[80] K. Liu, X. Hu, Z. Yang, et al. Lithium-ion battery charging management considering economic costs of electrical energy loss and battery degradation. Energy Conversion and Management, 2019, 195:167–179.

[81] T. Zhang, Q. Gao, G. Wang, et al. Investigation on the promotion of temperature uniformity for the designed battery pack with liquid flow in cooling process. Applied Thermal Engineering, 2017, 116:655–662.

[82] T.M. Bandhauer, S. Garimella, T.F. Fuller. A Critical Review of Thermal Issues in Lithium-Ion Batteries. Journal of The Electrochemical Society, 2011, 158:3515880

[83] M. Ikezoe, N. Hirata, C. Amemiya, et al. Development of high capacity lithium- ion battery for NISSAN LEAF. SAE Technical Papers, 2012, 01:104271.

[84] X. Tao, J. Wagner. A thermal management system for the battery pack of a hybrid electric vehicle: Modeling and control. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 2016, 230:190–201.

[85] J. Kim, J. Oh, H. Lee. Review on battery thermal management system for electric vehicles. Applied Thermal Engineering, 2019, 149:192–212.

[86] X. Tao, J. Wagner. A thermal management system for the battery pack of a hybrid electric vehicle: modeling and control. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 2015, 230:190–201.

[87] A.H. Mohammed, R. Esmaeeli, H. Aliniagerdroudbari, et al. Dual-purpose cooling plate for thermal management of prismatic lithium-ion batteries during normal operation and thermal runaway. Applied Thermal Engineering, 2019, 160:114106.

[88] Y. Lv, X. Yang, X. Li, et al. Experimental study on a novel battery thermal management technology based on low density polyethylene-enhanced composite phase change materials coupled with low fins. Applied Energy, 2016, 178:376–382.

[89] D. Kong, R. Peng, P. Ping, et al. A novel battery thermal management system coupling with PCM and optimized controllable liquid cooling for different ambient temperatures. Energy Conversion and Management, 2020, 204:112280.

[90] H. Sun, R. Dixon. Development of cooling strategy for an air cooled lithium-ion battery pack. Journal of Power Sources, 2014, 272:404–414.

[91] W.A. Hermann. Liquid cooling manifold with multi-function thermal interface. US, 2012, 12, 655995.

[92] S. Al Hallaj, J.R. Selman. A Novel Thermal Management System for Electric Vehicle

Batteries Using Phase-Change Material. Journal of The Electrochemical Society, 2000,147: 3231.

[93] J. E, D. Han, A. Qiu, et al. Orthogonal experimental design of liquid-cooling structure on the cooling effect of a liquid-cooled battery thermal management system. Applied Thermal Engineering, 2018, 132:508–520.

[94] M.A. Ashraf, C. Li, D. Zhang, et al. Battery thermal management with conjugate heat transfer in heat sink with Fe3O4/CNT-water nanofluid using lattice Boltzmann/finite volume method. Chemical Engineering and Processing - Process Intensification, 2019, 146:107708.

[95] M. Yates, M. Akrami, A.A. Javadi. Analysing the performance of liquid cooling designs in cylindrical lithium-ion batteries. Journal of Energy Storage, 2021, 33:100913.

[96] K.S. Reddy, V. Mudgal, T.K. Mallick. Review of latent heat thermal energy storage for improved material stability and effective load management. Journal of Energy Storage, 2018, 15:205–227.

[97] N. Tao, H. Hai. Application of Phase Change Material (PCM) in Concrete for Thermal Energy Storage. International Congress on Polymer in Concrete 2018, 2018, 17:187-193.

[98] J. Yan, K. Li, H. Chen, et al. Experimental study on the application of phase change material in the dynamic cycling of battery pack system. Energy Conversion and Management, 2016 , 128:12–19.

[99] F. Bai, M. Chen, W. Song, et al. Thermal management performances of PCM/water cooling-plate using for lithium-ion battery module based on non-uniform internal heat source. Applied Thermal Engineering, 2017, 126:17–27.

[100] H. Gao, J. Wang, X. Chen, et al. Nanoconfinement effects on thermal properties of nanoporous shape-stabilized composite PCMs: A review. Nano Energy, 2018, 53:769–797.

[101] C. Li, B. Xie, J. Chen, et al. Emerging mineral-coupled composite phase change materials for thermal energy storage. Energy Conversion and Management, 2019, 183:633–644.

[102] Q. Zhang, Y. Huo, Z. Rao. Numerical study on solid–liquid phase change in paraffin as phase change material for battery thermal management. Science Bulletin, 2016, 61:391–400.

[103] J.R. Patel, M.K. Rathod. Recent developments in the passive and hybrid thermal management techniques of lithium-ion batteries. Journal of Power Sources, 2020, 480:228820.

[104] M.M. Heyhat, S. Mousavi, M. Siavashi. Battery thermal management with thermal energy storage composites of PCM, metal foam, fin and nanoparticle. Journal of Energy Storage, 2020, 28:101235.

[105] S. Mousavi, M. Siavashi, M.M. Heyhat. Numerical melting performance analysis of a cylindrical thermal energy storage unit using nano-enhanced PCM and multiple horizontal fins, Numerical Heat Transfer; Part A: Applications, 2019, 75:560–577.

[106] W. Wu, J. Liu, M. Liu, et al. An innovative battery thermal management with thermally induced flexible phase change material. Energy Conversion and Management, 2020, 221: 113145.

[107] M. Pan, Y. Zhong. Experimental and numerical investigation of a thermal management system for a Li-ion battery pack using cutting copper fiber sintered skeleton/paraffin composite phase change materials. International Journal of Heat & Mass Transfer, 2018, 126:531–543.

[108] F. He, X. Li, G. Zhang, et al. Experimental investigation of thermal management system for lithium ion batteries module with coupling effect by heat sheets and phase change materials. International Journal of Energy Research, 2018, 42:101002.

[109] M. Ramzan, A. Hussain. Passive Cooling based Thermal Management System of Lithium-ion Batteries employing Copper foam/Paraffin Composite. ResearchGate, 2019.

[110] M.H. Shojaeefard, G.R. Molaeimanesh, Y.S. Ranjbaran. Improving the performance of a passive battery thermal management system based on PCM using lateral fins. Heat and Mass Transfer/Waerme- Und Stoffuebertragung, 2019, 55:1753–1767.

[111] C.J. Ho, S.T. Hsu, J.H. Jang, et al. Experimental study on thermal performance of water-based nano-PCM emulsion flow in multichannel heat sinks with parallel and divergent rectangular mini-channels. International Journal of Heat and Mass Transfer, 2020,146: 118861.

[112] S. Mousavi, M. Siavashi, A. Zadehkabir. A new design for hybrid cooling of Li-ion battery pack utilizing PCM and mini channel cold plates. Applied Thermal Engineering, 2021,197 :117398.

[113] H. He, H. Jia, W. Huo, et al. Field synergy analysis and optimization of the thermal behavior of lithium ion battery packs. Energies, 2017, 10:81.

[114] T. Yamanaka, D. Kihara, Y. Takagishi, et al. Multi-physics equivalent circuit models for a cooling system of a lithium ion battery pack. Batteries, 2020, 6:1–19.

[115] J. Liang, Y. Gan, Y. Li, et al. Thermal and electrochemical performance of a serially connected battery module using a heat pipe-based thermal management system under different coolant temperatures. Energy, 2019, 189:1-16.

[116] W. Wu, X. Yang, G. Zhang, et al. Experimental investigation on the thermal performance of heat pipe-assisted phase change material based battery thermal management system. Energy Conversion and Management, 2017, 138:486–492.

[117] X.-H. Yang, S.-C. Tan, Z.-Z. He, et al. Finned heat pipe assisted low melting point metal PCM heat sink against extremely high power thermal shock. Energy Conversion and Management, 2018, 160:467–476.

[118] J. Kim, J. Oh, H. Lee. Review on battery thermal management system for electric vehicles. Applied Thermal Engineering, 2019, 149:192–212.

[119] Y.-R. Ji, S.-T. Weng, X.-Y. Li, et al. Atomic-scale structural evolution of electrode materials in Li-ion batteries: a review. Rare Metals, 2020, 39 : 205–217.

[120] S.W.D. Gourley, Z. Chen. Recycling of mixed cathode lithium - ion batteries for electric vehicles : Current status and future outlook. Carbon Energy, 2020, 101002.

[121] H. Teng, K. Yeow. Design of direct and indirect liquid cooling systems for high-capacity, high-power lithium-ion battery packs. SAE International Journal of Alternative Powertrains. 2012, 1:525–536.

[122] M. Shen, Q. Gao. System simulation on refrigerant-based battery thermal management technology for electric vehicles. Energy Conversion and Management, 2020, 203:112176.

[123] I.L. Krüger, D. Limperich, G. Schmitz. Energy Consumption of Battery Cooling In Hybrid Electric Vehicles. International Refrigeration and Air Conditioning Conference, 2012:1–10.

[124] M. Hamid Elsheikh, D.A. Shnawah, M.F.M. Sabri, et al. A review on thermoelectric renewable energy: Principle parameters that affect their performance. Renewable and Sustainable Energy Reviews, 2014, 30:337–355.

[125] J. Kim, J. Oh, H. Lee. Review on battery thermal management system for electric vehicles. Applied Thermal Engineering, 2019, 149:192–212.

[126] L.T. Yeh, R.C. Chu. Thermoelectric Coolers. John Wiley & Sons, Ltd, 2010, 801683.

[127] Y. Liu, S. Yang, B. Guo, C. Deng. Numerical Analysis and Design of Thermal Management System for Lithium Ion Battery Pack Using Thermoelectric Coolers. Advances in Mechanical Engineering, 2014, 8:852712.

[128] Y. Troxler, B. Wu, M. Marinescu, et al. The effect of thermal gradients on the performance of lithium-ion batteries. Journal of Power Sources, 2014, 247:1018–1025.

[129] G. Liao, K. Jiang, F. Zhang, et al. Thermal performance of battery thermal management system coupled with phase change material and thermoelectric elements State of Charge. Journal of Energy Storage, 2021, 43:103217.

[130] Y. Lyu, A.R.M. Siddique, S.H. Majid, et al. Electric vehicle battery thermal management system with thermoelectric cooling. Energy Reports, 2019, 5:822–827.

[131] G. Zhong, B. Mao, C. Wang, et al. Thermal runaway and fire behavior investigation of lithium ion batteries using modified cone calorimeter. Journal of Thermal Analysis and

Calorimetry. 2019, 135:2879–2889.

[132] P. Wang, Z. Gong, K. Ye, et al. Design and construction of a three - dimensional electrode with biomass - derived carbon current collector and water - soluble binder for high - sulfur - loading lithium - sulfur batteries, 2020, 49:1–11.

[133] G. Wang, G. Zhao, H. Li, et al. Multi-objective optimization design of the heating/cooling channels of the steam-heating rapid thermal response mold using particle swarm optimization. International Journal of Thermal Sciences, 2011, 50:790–802.

[134] S. Wu, R. Xiong, H. Li, et al. The state of the art on preheating lithium-ion batteries in cold weather. Journal of Energy Storage, 2020, 27:101059.

[135] J. Guo, F. Jiang. A novel electric vehicle thermal management system based on cooling and heating of batteries by refrigerant. Energy Conversion and Management, 2021, 237:114145.

[136] S.F. Huang, Y. Lv, D. Tie, et al. Realizing simultaneously enhanced energy and power density full-cell construction using mixed hard carbon/Li4Ti5O12 electrode. Rare Metals, 2021, 40:65-71.

[137] X. Liu, D. Ren, H. Hsu, et al. Thermal Runaway of Lithium-Ion Batteries without Internal Short Circuit. Joule, 2018, 2:2047–2064.

[138] G. Karimi, X. Li. Thermal management of lithium-ion batteries for electric vehicles. International Journal of Energy Research, 2013, 37:13–24.

[139] L.I. Gang, X. Huang, X.N. Feng, et al. Design Research on Battery Heating and Preservation System Based on Liquid Cooling Mode. Hunan Daxue Xuebao/Journal of Hunan University Natural Sciences, 2017, 44:26–33.

[140] A. Pesaran. Battery Thermal Management in EVs and HEVs: Issues and Solutions, Battery Man, 2001,43.

[141] R. Matthé, U. Eberle. The Voltec System-Energy Storage and Electric Propulsion. Elsevier. 2014, 38:151-176.

[142] R. Matthe, L. Turner, H. Mettlach. VOLTEC Battery System for Electric Vehicle with Extended Range. SAE International Journal of Engines, 2011,4:1944–1962.

[143] P. Chen, Z. Lu, L. Ji, et al. Design of the Control Scheme of Power Battery Low Temperature Charging Heating Based on the Real Vehicle Applications, in: Vehicle Power & Propulsion Conference, 2013.

[144] J.B. Straubel, E. Berdichevsky, D. Lyons, et al. Battery mounting and cooling system. BATTERY MODULE, 2015, 14:706837.

[145] X. Hu, Y. Zheng, D.A. Howey, et al. Battery warm-up methodologies at subzero temperatures for automotive applications: Recent advances and perspectives. Progress in

Energy and Combustion Science, 2020, 77:100806.

[146] Z.H. Rao, S.F. Wang, Y.L. Zhang. Thermal management with phase change material for a power battery under cold temperatures. Energy Sources, Part A: Recovery, Utilization and Environmental Effects, 2014, 36:2287–2295.

[147] J. Song-Lin, G. Hong-Zhang, W. Luda, et al. Carbon nanotube-based flexible electrothermal film heaters with a high heating rate. National Library of Medicine, 2018, 5:172072.

[148] Y. Wang, X. Zhang, Z. Chen. Low temperature preheating techniques for Lithium-ion batteries: Recent advances and future challenges. Applied Energy, 2022, 313:118832.

[149] A. Pesaran, A. Vlahinos, T. Stuart. Cooling and preheating of batteries in hybrid electric vehicles, in: 6th ASME-JSME Thermal Engineering Joint Conference, 2003, pp. 1–7.

[150] C.Y. Wang, G. Zhang, S. Ge, et al. Lithium-ion battery structure that self-heats at low temperatures. Nature, 2016, 529:515–518.

[151] C.-Y. Wang, T. Xu, S. Ge, et al. A Fast Rechargeable Lithium-Ion Battery at Subfreezing Temperatures. Journal of The Electrochemical Society, 2016, 163:A1944–A1950.

[152] C.Y. Wang, G. Zhang, S. Ge, et al. Lithium-ion battery structure that self-heats at low temperatures. Nature, 2016, 529:515–518.

[153] R. Xiong, J. Cao, Q. Yu, et al. Critical Review on the Battery State of Charge Estimation Methods for Electric Vehicles. IEEE Access, 2018, 6: 1832–1843.

[154] J. Jaguemont, L. Boulon, Y. Dubé. A comprehensive review of lithium-ion batteries used in hybrid and electric vehicles at cold temperatures. Applied Energy, 2016,164:99–114.

[155] Y. Ji, C.Y. Wang. Heating strategies for Li-ion batteries operated from subzero temperatures. Electrochimica Acta, 2013, 107:664–674.

[156] J. Zhang, H. Ge, Z. Li, et al. Internal heating of lithium-ion batteries using alternating current based on the heat generation model in frequency domain. Journal of Power Sources, 2015, 273:1030–1037.

[157] T.A. Stuart, A. Hande, HEV battery heating using AC currents. Journal of Power Sources, 2004, 129:368–378.

[158] Z. LEI, C. ZHANG, J. LI, et al. Preheating method of lithium-ion batteries in an electric vehicle. Journal of Modern Power Systems and Clean Energy, 2015, 3:289–296.

[159] X. Wu, L. Li, J. Du. Preheating strategy of variable-frequency pulse for lithium battery in cold weather. International Journal of Energy Research, 44, 2020:10724–10738.

[160] Z. Liao, S. Zhang, K. Li, et al. A survey of methods for monitoring and detecting thermal runaway of lithium-ion batteries. Journal of Power Sources, 2019, 436:226879.

[161] S. Ge, Y. Leng, T. Liu, et al. A new approach to both high safety and high performance of lithium-ion batteries. Science Advances, 2020, 6:7633.

[162] C. Xu, J. Jiang. Designing electrolytes for lithium metal batteries with rational interface stability. Rare Metals, 2020, 23:99–101.

[163] K. Liu, W. Liu, Y. Qiu, et al. Electrospun core-shell microfiber separator with thermal-triggered flame-retardant properties for lithium-ion batteries. Science Advances, 2017, 3:1601978.

[164] Z. Chen, P.C. Hsu, J. Lopez, et al. Fast and reversible thermoresponsive polymer switching materials for safer batteries. Nature Energy, 2016, 1:15009.

[165] X. Li, Z. Wang. A novel fault diagnosis method for lithium-Ion battery packs of electric vehicles. Measurement, 2018,116:402–411.

[166] J. Zhu, X. Zhang, H. Luo. Investigation of the deformation mechanisms of lithium-ion battery components using in-situ micro tests. Applied Energy, 2018, 224:251–266.

[167] R. Wang. Lithium ion battery failure detection using temperature difference between internal point and surface, Dissertations & Theses Gradworks. 2011.

[168] R. Srinivasan, P.A. Demirev, B.G. Carkhuff. Rapid monitoring of impedance phase shifts in lithium-ion batteries for hazard prevention. Journal of Power Sources, 2018, 405:30–36.

[169] Andriy Kvasha, C. Gutiérrez, U. Osa, et al. A comparative study of thermal runaway of commercial lithium ion cells. Energy, 2018, 159, 547-557.

[170] D.P. Finegan, M. Scheel, J.B. Robinson, et al. Investigating lithium-ion battery materials during overcharge-induced thermal runaway: an operando and multi-scale X-ray CT study. Physical Chemistry Chemical Physics, 2016, 18:30912-30919.

[171] W. Luo, S. Zhu, J. Gong, et al. Research and Development of Fire Extinguishing Technology for Power Lithium Batteries. Procedia Engineering, 2018, 211:531–537.

[172] L. Zhang, Y. Li, Q. Duan, et al. Experimental study on the synergistic effect of gas extinguishing agents and water mist on suppressing lithium-ion battery fires. Journal of Energy Storage, 2020, 32:101801.

[173] L. Zhang, Q. Duan, Y. Liu, et al. Experimental investigation of water spray on suppressing lithium-ion battery fires. Fire Safety Journal, 2021, 120:103117.

[174] Y. Liu, Q. Duan, J. Xu, et al. Experimental study on a novel safety strategy of lithium-ion battery integrating fire suppression and rapid cooling. Journal of Energy Storage, 2020, 28 :101185.

[175] J. Weng, D. Ouyang, X. Yang, et al. Alleviation of thermal runaway propagation in thermal management modules using aerogel felt coupled with flame-retarded phase change material.

Energy Conversion and Management, 2019, 200:112071.

[176] Y. Huang, Y. Wu, B. Liu. Experimental investigation into the use of emergency spray on suppression of battery thermal runaway. Journal of Energy Storage, 2021, 38:102546.

[177] Q. Gao, Y. Liu, G. Wang, et al. An experimental investigation of refrigerant emergency spray on cooling and oxygen suppression for overheating power battery. Journal of Power Sources, 2019, 415:33–43.

[178] C. Jin, Y. Sun, H. Wang, et al. Model and experiments to investigate thermal runaway characterization of lithium-ion batteries induced by external heating method. Journal of Power Sources, 2021, 504:230065.

[179] D. Ren, L. Xiang, X. Feng, et al. Model-based thermal runaway prediction of lithium-ion batteries from kinetics analysis of cell components. Applied Energy, 2018, 228:633–644.

[180] S. Abada, M. Petit, A. Lecocq, et al. combined experimental and modeling approaches of the thermal runaway of fresh and aged lithium-ion batteries. Journal of Power Sources, 2018, 399:264-273.

[181] X.G. Yang, G. Zhang, S. Ge. Fast charging of lithium-ion batteries at all temperatures. Proceedings of the National Academy of Sciences of the United States of America, 2018, 115:7266–7271.

[182] W. Li, M. Rentemeister, J. Badeda, et al. Digital twin for battery systems: Cloud battery management system with online state-of-charge and state-of-health estimation. Journal of Energy Storage, 2020, 30:101557.

[183] Z. Zhang, W. Ma, F. Li, et al. An Attention-Enhanced Edge-Cloud Collaborative Framework for Multi-Task Application, in: 2021, 2021, 49: 9359693

[184] S. Yang, R. He, Z. Zhang, et al. CHAIN: Cyber Hierarchy and Interactional Network Enabling Digital Solution for Battery Full-Lifespan Management. Matter, 2020, 3:27–41.

[185] B. Wu, W.D. Widanage, S. Yang, et al. Battery digital twins: Perspectives on the fusion of models, data and artificial intelligence for smart battery management systems. Energy and AI, 2020,1:100016.

[186] M.S. Aslanpour, S.S. Gill, A.N. Toosi. Performance evaluation metrics for cloud, fog and edge computing: A review, taxonomy, benchmarks and standards for future research. Internet of Things, 2020, 12:100273.

[187] A. Sy, A. Zz, C.A. Rui, et al. Implementation for a cloud battery management system based on the CHAIN framework. Energy and AI. 2021,5:100088.

[188] Y. wei Pan, Y. Hua, S. Zhou, et al. A computational multi-node electro-thermal model for large prismatic lithium-ion batteries. Journal of Power Sources, 2020, 459:228070.