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Review

A review on recent progress, challenges and perspective of battery thermal management system

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ABSTRACT

New energy vehicles have significant prospects in reducing greenhouse gas emission and environmental pollution. Lithium-ion batteries are the favored power source in electric vehicles because of their high energy density and long service life. The battery performance depends noticeably on the temperature. Battery thermal management system, which can keep the battery pack working in a proper temperature range, not only affects significantly the battery pack system performance but is also vital for the safety and stability. This article mainly summarizes the thermal management models in the literature which can predict heat generation, heat transfer and the temperature distribution within the battery cell, module and pack. The multi-physical battery thermal management systems are divided into three categories based on different methods of cooling the phase change materials such as air-cooled system, liquid-cooled system, and heat-pipe-cooled system. The emergency battery thermal battier methods are also summarized in multi-scale included material scale, battery management system and supplementary system. Finally, we propose a novel digital solution for full-lifespan thermal management control of EV power system based on CHAIN framework that helps improve the power battery temperature control strategy applying multiple working conditions.

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1. Introduction

Electric vehicles (EV) have great potential benefits to reduce greenhouse gas (GHG) emission and environmental pollution. As the banning of sales of conventional fuels was proposed by European Union in 2011, deadlines to stop conventional fuel vehicle manufacturing have been announced sequentially by China, French, British, Norway, and other countries [1]. Meanwhile, funding and policies are set up to support the development of EV [2–6]. For example, European and Chinese governments are providing subsidies to promote the EV sales according to the vehicle price and greenhouse gas emission level. Meanwhile, most European countries offer high ratio (mostly 50% to 75%) of installation subsidies of charging piles for private and public parking areas. The International Energy Agency (IEA) also predicts in Nordic EV outlook 2018 that the EV will reach 1.3 million units by 2030 based on the current market development trend [7].

With the rapid growth of EV, the demand for power batteries with high energy density has been increasing fast [8–10]. Compared with other types of energy storages [11–13] lithium-ion batteries (LIB) are favored in new energy vehicles due to their low self-discharge rate, long service life, high power and energy densities [14,15]. Recent researches indicate that lithium ion battery will continue to improve in cost, safety, energy and power capability and will keep standing out from the rest batteries in the next several years. However, degradation and thermal safety of LIB are still the major challenges for the development of the LIB and LIB-powered EV [16–20]. Studies have shown that the capacity [21–24], cycle life [25–28] and safety [4,29,30] of power battery depends highly on the temperature. The performance and stability of LIB decline fast at the abnormal temperature range for almost all cell materials. If the temperature is too low, the battery capacity will be significantly reduced [17] due to the lithium plating at high rate charging [21] /discharging [22]; High temperature will accelerate battery side reactions [31] and degradation. For example, the

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Nomenclature

v	Velocity ($m \cdot s^{-1}$)
q	Heat generation rate ($j \cdot s^{-1}$)
T	Temperature (K)
h	Convection coefficient ($J \cdot m^{-2} \cdot s^{-1} \cdot K^{-1}$)
A	Surface area (m^2)
c	Heat capacity ($J^{-1} \cdot kg \cdot K^{-1}$)
I	Electric current (A)
U	Open-circuit voltage(V)
V	Cell voltage (V)
$\vec{V}$	Velocity vector (ms^{-1})
g	Gravitational body Force ($m \cdot s^{-2}$)
F	External body forces($m \cdot s^{-2}$)
H	Enthalpy ($J \cdot kg^{-1}$)
L	Heat of fusion (J)
f	Fraction (N)
t	Time (s)
P	Static pressure (Pa)
Re	Reynold number
Greek symbols	
ρ	Density ($kg \cdot m^{-3}$)
λ	Thermal conductivity ($W \cdot m^{-2} \cdot K^{-1}$)
μ	Dynamic viscosity ($kg \cdot m^{-1} \cdot s^{-1}$)
θ	Integration variable
Subscripts	
e	Electrolyte
P	Phase change material; Also pressure
f	Fluid
s	Solid; Also surroundings
Ref	Reference value
Eff	Effective
Acronyms	
EV	Electric vehicles
GHG	Greenhouse gas
IEA	International Energy Agency
LIB	Lithium-ion batteries
BTMS	Battery thermal management system
EBTB	Emergency battery thermal barrier
PCM	Phase change material
2D	Two dimensions
3D	Three dimensions
CM	Carbonaceous materials
EG	Expanded graphite
LTNE	local thermal non-equilibrium
BMS	Battery management system
SOC	State of charge
SOH	State of health
SOP	State of power
V2X	Vehicle to everything
SEI	Solid electrolyte interphase
PID	Proportional integral derivative
OHP	Oscillating heat pipe
TAP	Triallyl phosphate
TPP	Triphenyl phosphate
CHAIN	Cyber Hierarchy And Interactional Network
ETNN	Electrochemical thermal neural network

solid electrolyte interphase (SEI) layer on the anode grows faster at high temperatures, becoming more porous and unstable during fast charging [32]; Manufacturing defect parts such as holes on the separator may be overheated [29]. Feng et al. [33] also revealed that the local overheat is one of abuse conditions included mechanical abuse, electrical abuse, and thermal abuse to trigger thermal runaway. Thermal runaway, a kind of serious safety problem, follows a mechanism of chain reactions, during which the decomposition reaction of the battery component materials occurs one after another which may induce smoke, fire, and even explosion, threatening lives of the drivers and passengers.

Therefore, efficient battery thermal management system (BTMS) is essential to keep battery temperature within the proper range and to decrease the temperature variance between cells [34,35]. There are two main criteria to evaluate the performance of the BTMS: the maximum temperature rise and the maximum temperature difference of the battery pack. To maintain optimal performance and to prolong the lifespan of the power battery, the temperature of all the cells need to be maintained within a narrow range between 20 °C and 45 °C, and the maximum temperature difference among cells should be less than 5 °C under wide range of C-rates [36]. C-rate is the measurement of charge and discharge current with respect to its nominal capacity which is related to the working condition of EV. The latest key metric of cooling coefficient proposed by Gregory [37] can be used to describe the temperature gradient across a cell in operation. It can inform a designer the ability of the heat generation and transfer and how difficult the thermal management will be in the selected cells in a pack.

The BTMS can be classified into preheating BTMS, cooling BTMS and emergency battery thermal barrier (EBTB). Hu et al. [38] summarized the preheating BTMS comprehensively which is used to preheat the battery pack in the case of cold working condition. The preheating BTMS is composed of convective and conductive preheating. The convective preheating BTMS consists of air heating, liquid heating, and heat pump heating. The conductive preheating BTMS consists of resistance heating, Peltier-effect heating, heat pipe heating, burner heating and phase change material (PCM) heating. The cooling BTMS [6] is divided into air cooling [39], liquid cooling [40], heat pipe cooling [41,42], coolant direct cooling [43], boiling cooling [44,45] and phase change material (PCM) cooling [46]. These cooling methods are combined to multi-physical system to ensure both the maximum temperature rise and the maximum temperature difference are maintained in the proper range. EBTB is designed to minimize the potential hazards to the driver and passengers and the damage to the battery pack to reduce economic loss when the thermal runaway is predicted to occur [47]. In addition to the survey of different BTMS designs, the thermal theories such as heat generation, heat transfer, and heat dissipation in power battery are also reviewed. Battery models such as the electrochemical-thermal-mechanical coupled model and multi-node thermal model for cells, modules, packs and other multi-dimensional models have been developed through theoretical derivation and experiments to predict the battery pack temperature.

The previous BTMS review papers mostly focused on heat exchange method [48–52] or materials [18,53–55] and there was limited discussion on battery thermal barrier and the future direction of BTMS. This paper aims to review the existing work and look forward to future developments of BTMS based on the latest research. Specifically, an overview of the electrical and thermal models of LIB is provided. The multi-physical cooling BTMS performances characterized by maximum temperature rise and maximum temperature variance are summarized and different optimization methods are compared. Different multi-scale EBTBs are presented and the trigger conditions are also detailed. Finally, a new novel digital solution for full-lifespan thermal management control of EV power system based on CHAIN Control System framework is proposed to improve the performance of the BTMS.

2. Thermal models and issue

2.1. LIB thermal models

The LIB's performance is closely related to temperature, so it is important to understand the thermal dynamics of the battery [56]. Huang et al. [57] reported a method of in situ measurement of pouch cell internal temperatures. However, temperature measured by thermocouple can only obtain the mid-point temperature, not the internal temperature distribution. The in-situ monitoring of the battery internal temperature is still challenging [58]. Simulation based on thermal models is usually used to study on the battery internal temperature distribution and reduce the experimental cost.

Cell-level thermal models can be classified into electro-thermal model [59], electrochemical thermal model [60] and thermal runaway propagation model [61] according to the physical mechanism (Table 1). These models can also be categorized as lumped model [60], 1D axial symmetry [62], 2D [63] and 3D [64] according to the dimensions.

The thermal model includes heat generation and heat transfer, as shown in (Eq. (1)) [50], and the heat generation is strongly related to the electrochemical reaction rate occurring inside the cell during charge and discharge. The cell temperature is solved by heat transfer equation as shown in (Eq. (1))

$$\rho c_p\left(\frac{\partial T}{\partial t}+\upsilon_e\cdot\nabla T\right)\approx\frac{\partial(\rho c_p T)}{\partial t}=\nabla\cdot\lambda\nabla T+q \tag{1}$$

where ρ is the average density of the battery. c_p is the average heat capacity under constant pressure. v_e is the electrolyte velocity. λ is the average thermal conductivity in all directions. q is the heat generation rate. It is worth noting that the term $\upsilon\cdot\nabla T$ which is the internal convective heat transfer is usually neglected due to the limited mobility of the liquid electrolyte of the LIB [65].

The lumped thermal model considers the heat transfer between the battery and the surroundings, as in Eq. (2). It assumes that the heat transfer of battery is uniformly distributed in all directions and is usually used in cells with small thickness [32].

$$\frac{d(\rho c_p T)}{dt}=hA_s(T-T_\infty)+q \tag{2}$$

where h is the convection coefficient. A_s is the surface area of cell exposed to the surroundings. T_∞ is the temperature of the cooling medium.

The heat generation of LIB consists of reversible and irreversible heat. Bernardi et al. obtained the simplified LIB heat generation equation from experiment as follows, [66]

$$q=I(U-V)-I\left(T\frac{dU}{dT}\right) \tag{3}$$

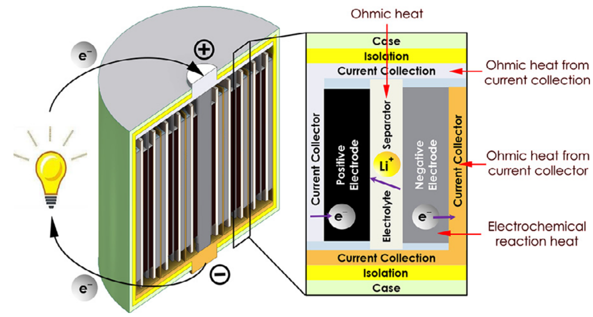

Fig. 1. Schematic of heat generation and transfer of LIB.

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 term *I(U-V)* represents irreversible heat caused by the resistance in the cell. *U-V* represents the total internal overpotential of the battery induced by processes such as the charge transfer reactions at the electrode/electrolyte interfaces, the diffusion and migration of Li ion across the electrolyte and electrodes, and the ohmic losses. The second term $I(T\frac{dU}{dT})$ is the reversible entropic heat during the electrochemical reaction [67]. Fig. 1 details the heat generation and transfer of different parts of LIB.

Effective battery thermal models can predict the temperature distribution of cells, modules and packs under different charging/discharging patterns [3,62–64,68,69]. Based on electro-thermal model, sub-models such as impedance-based model of overcharging process and capacity fade model, are added to improve the accuracy of the prediction of the temperature distribution [21,61,70]. Xie et al. [64]. also took the battery body and the current collecting posts into account in the thermal model, and the maximum average error of temperature estimation was 1.23 °C. Feng et al. [71] formulated an electrochemical-thermal-neural-network (ETNN) model. The temperature prediction error is less than 0.7 °C when the battery temperature varies between 20 and 40 °C. Pan et al. [5] established a heat generation model based on a second-order equivalent-circuit model and a novel multi-node heat transfer model based on the battery geometry as shown in Fig. 2. The maximum temperature prediction error is less than 2 °C throughout the experimental cycles, while the computational cost is reduced by 90% compared with electrochemical model. The proposed model holds a great potential for online temperature estimation in advanced lithium-ion BTMS design.

As to the thermal model of the battery module and pack, the heat transfer analysis and thermal gradient are key limiting factors for lifetime and cost. Jeong et al. [72] found that anisotropic heat conduction due to the stacked geometry of the unit cells caused temperature non-uniformity within the battery module. Further research by Liu et al. [73] investigated the degradation of battery pack caused by thermal gradient using the SEI growth model. It was shown that the thermal gradient can further cause current heterogeneity leading to accelerated local aging. However, the

Table 1
Comparation of different thermal model.

Model	Reference	Advantage	Disadvantage
Electrochemical-thermal model	[3,21,56,60,62,67,70,71,76–78]	Thermal properties can improve computational accuracy.	The system model size is limited because of practical computational time.
Electro-thermal model	[5,59,63,79–81]	Minimal computational effort is required since the LIB model is simplified [65].	It is potentially less accurate since the LIB model just computes an average temperature for the entire chemistry.
Thermal runaway propagation model	[34,61,67,82,83]	It can predict thermal runaway propagation within a large format lithium ion battery module [74].	The computational cost is also high just like the electrochemical-thermal model.

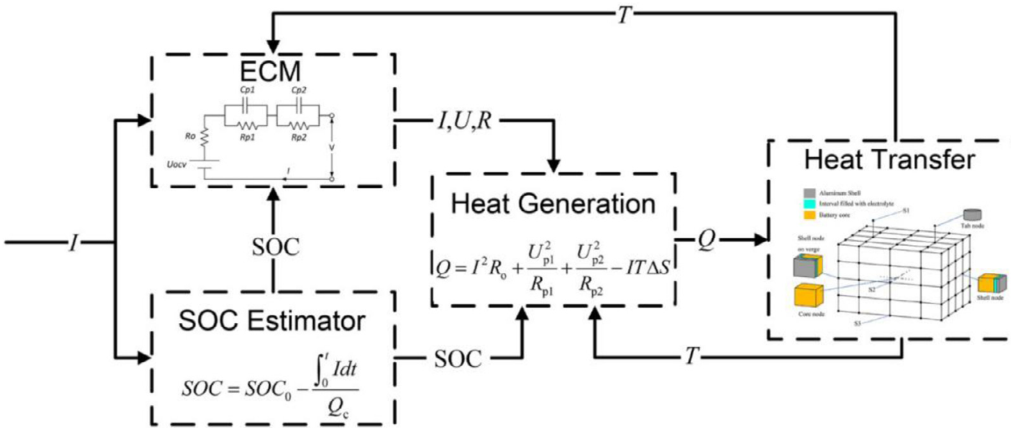

Fig. 2. Schematic illustration of the multi-node electro-thermal model [5].

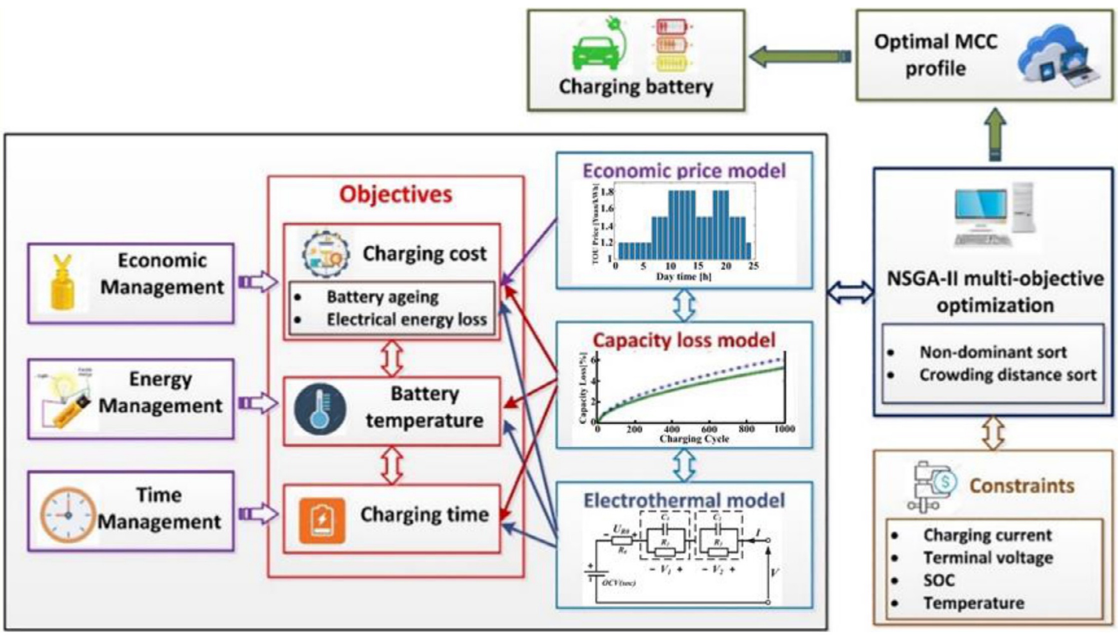

Fig. 3. Overall multi-objective optimization framework for economic-conscious charging [75].

above work just aimed to optimize estimation accuracy of temperature and did not consider the economic factors. Feng et al. [74] put forward a thermal runaway propagation model which can fit experiment data well. The modeling analysis can provide substantial quantified solutions to prevent TR propagation. Liu et al. [75] proposed a constrained multi-objective optimization framework to develop economy-conscious charging management. Specifically, the economic indicator of the total charging cost, which includes both the battery aging cost and electrical energy loss, is minimized based on a coupled electrothermal-aging model with different timescales (Fig. 3). This study shows that small values of the cut-off voltage, heat convection resistance and ambient temperature can reduce the temperature rise and economic charging cost while sacrificing charging speed.

2.2. Coolant thermal model

2.2.1. Fluid coolant thermal model

Cooling BTMS is used to protect the battery from high temperature. Air and liquid are commonly used coolant due to the low cost, simple structure, high stability and good ability of heat transfer [51y. The model is built on the three fundamental equations, i.e., the continuity equation (Eq. (4)), the momentum equation (Eq. (5)) and the energy equation (Eq. (6)) [84]. Incompressible condition is usually assumed because the fluid velocity is low [50].

$$\nabla \cdot \vec{V} = 0 \tag{4}$$

$$\frac{\partial \vec{V}}{\partial t} + \left(\vec{V} \cdot \nabla\right)\vec{V} = -\frac{\nabla P}{\rho_f} + \frac{\mu}{\rho_f}\nabla^2\vec{V} + g + F \tag{5}$$

$$\rho_f \cdot c_p \cdot \left(\frac{\partial T}{\partial \tau} + u \cdot \frac{\partial T}{\partial x} + v \cdot \frac{\partial T}{\partial y} + w \cdot \frac{\partial T}{\partial z}\right) = \lambda_f \cdot \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + q \tag{6}$$

where ρ_f, λ_f and c_p are the density, thermal conductivity and specific heat of the coolant. $\vec{V}$ is the velocity vector of the coolant, μ is the dynamic viscosity, P is the static pressure, g and F are the gravitational body force and external body forces and q is the heat generation rate.

The cooling performance of the BTMS depends strongly on the flow pattern [85–90] and flow rate [40,91], which can be optimized

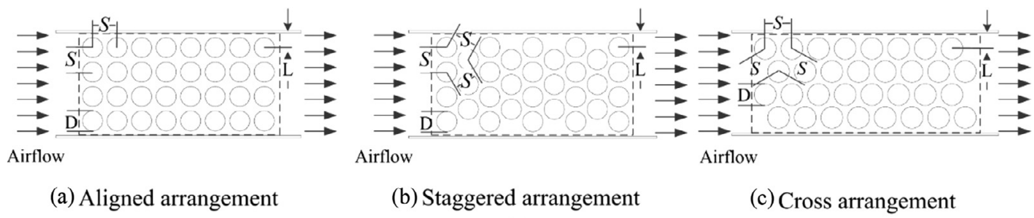

Fig. 4. Structural projections of the replaceable battery packs [9].

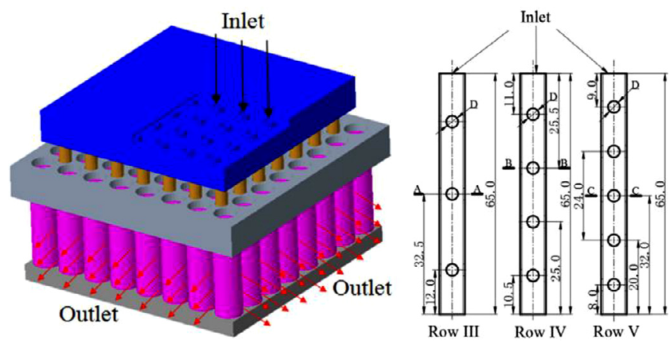

Fig. 5. Schematics of the battery module with air distribution pipes [96].

based on the 2D [92] and 3D [10] models. However, the fabrication cost of complicated flow pattern can be prohibitively high, and therefore a reduction of computational expense is necessary [93]. Researchers [94,95] have found that the symmetrical BTMS can achieve much better cooling performance than the corresponding asymmetrical design. Fan et al. [9] found that the aligned arrangement has the best cooling performance in terms of temperature uniformity as shown in Fig. 4. Zhou et al. [96] proposed a new air flow pattern (Fig. 5) which can reduce the battery temperature variance.

Ashraf et al. [92]. found that the top and bottom walls with Zigzag configurations can increase the heat transfer performance due to the formation of the eddy which enhances the mixing of fluid. Zhang et al. [97] added a piece of flexible graphite between the battery and the flow channel in order to improve temperature uniformity of the battery pack as shown in Fig. 6. Chung et al. [98] presented a thermal model for the liquid-cooling pouch battery pack with 7500 cells which can give a detailed thermal analysis of various pack designs. Rao's group [99] designed a type of liquid cooling method based on mini-channel cold-plate as shown in Fig. 7. The results showed that temperature uniformity was significantly improved and temperature difference decreased 43.3%.

The multi-objective optimization algorithms have also been used to optimize the coolant flow pattern [100-102] and to improve the cooling control strategy [103] which keeps the battery pack within the optimal range (25–40 °C) and maintains a low temperature variance between cells (less than 5 °C). Ma et al. [103] proposed an optimal design method for the cooling BTMS for lithium-ion batteries based on a three-step nonlinear optimization method. The triple-step nonlinear optimization method (Fig. 8) and proportional integral derivative (PID) control method are compared under different operating conditions. The simulation results show that the triple-step nonlinear method can keep the battery temperature under 32 °C and the deviation from the target temperature is lower than 2.0 °C. The new method also improves the speed of the cooling process of lithium-ion batteries.

The flow rate control by adjusting the pump speed can improve the cooling performance in active air/liquid cooling system under a wide range of charging/discharging conditions [104]. However, the power loss caused by pump reduces the efficiency of the battery pack. Therefore, new adaptive control methods have been developed in recent research [11]. Liu et al. [79,105] established a self-adaptive intelligent neural network-based model predictive control strategy for a J-type air-based BTMS using surrogate-based optimization algorithm (Fig. 9), which can maintain the temperature variance under 1.33 K while increasing the energy efficiency by 15.8%.

2.2.2. PCM coolant thermal model

Apart from air and liquid, PCM is another efficient coolant due to its high heat latent. Although the PCM's cooling speed is lower than fluid cooling at high temperature, it can reduce the temperature variance dramatically which can reduce degradation of the battery pack [106,107]. Under the phase-change temperature, heat is transferred from the cells to the solid PCM by conduction. After the battery temperature reaches the melting point, the PCM can absorb a large amount of heat flux from the battery (Fig. 10). As a result, the temperature of every cell in the pack can be kept the same, equal to the melting point [53]. Klimeš et al. [108] summarized the two widely used methods for modeling the heat transfer of PCM, i.e., the enthalpy method and the effective heat capacity method.

The enthalpy method uses enthalpy which is a thermodynamic function to describe the relationship between sensible heat and latent heat during the phase change. The enthalpy H can be defined as a function of temperature T as

$$H(T) = \int_{T_{ref}}^{T} \left(\rho_P c - \rho_P L \frac{\partial f_s}{\partial \theta} \right) d\theta \tag{7}$$

where H is enthalpy, ρ_P is the density, T_{ref} is a reference temperature, c is the heat capacity, L is the heat of fusion, f_s is the solid fraction, and θ is integration variable. Then the enthalpy H is substituted into heat transfer function (Eqn. (7)) to solve the heat transfer problem with phase change

$$\frac{\partial H}{\partial t} = \nabla \cdot (\lambda_P \nabla T) \tag{8}$$

where t is time, λ_P is the thermal conductivity. The enthalpy method can deal with both sharp and gradual phase change, and the computation efficiency is high. However, it is difficult to handle supercooling problems [109].

The equations of the effective heat capacity method are given as follows.

$$c_{eff}(T) = \frac{1}{\rho_P} \frac{\partial H}{\partial T} \tag{9}$$

$$\rho c_{eff} \frac{\partial T}{\partial t} = \nabla \cdot (\lambda_P \nabla T) \tag{10}$$

where c_{eff} is the effective heat capacity.

The effective heat capacity method is concise, and only one dependent variable 'Temperature' needs to be calculated. However, small time step and fine grids are required to achieve a desirable accuracy, which comes with a high computational cost compared with the enthalpy method [109].

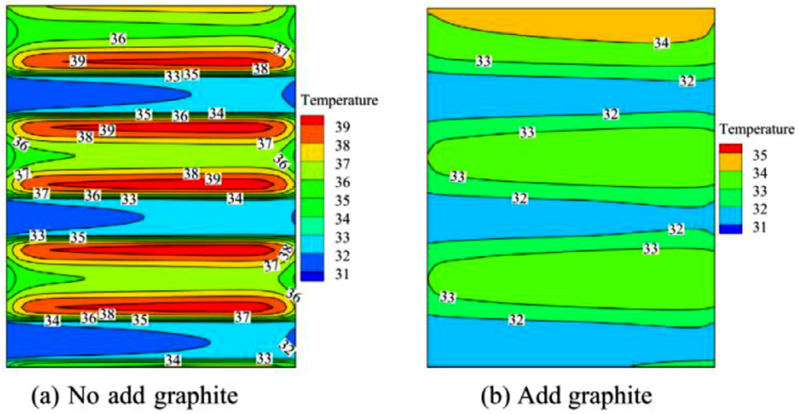

Fig. 6. The battery surface temperature distribution in cooling equilibrium state [97].

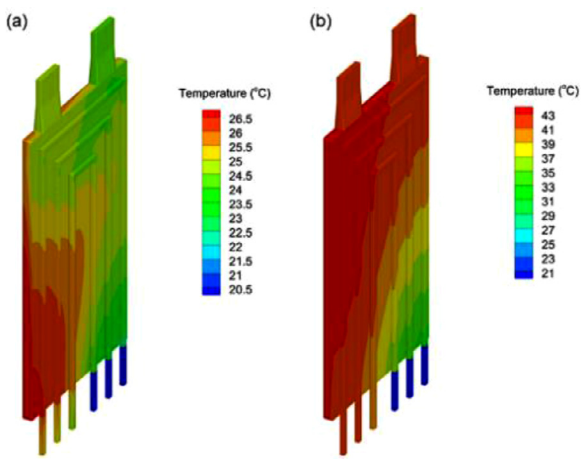

Fig. 7. Thermal management system using mini-channel cooling [99].

Selecting the appropriate phase change material is the first step of building the PCM system. The PCM needs to satisfy the following six requirements: [50]

(a) The melting point within the desirable temperature scope;
(b) High latent heat, high specific heat capacity and high thermal conductivity;
(c) Low volume dilatation after phase change process;
(d) Negligible sub-cooling effect when freezing;
(e) Properties including stable, nontoxic, nonflammable and non-explosive;
(f) Commercially economical.

Most pure PCM has low thermal conductivity. The cooling performance of PCM can be greatly enhanced by improving the thermal conductivity [54,110,111]. The most commonly used method is introducing a metallic component as the thermal conductive framework [42,112]. Nanomaterials such as nanosilic [113,114] and powder-like carbonaceous materials (CM), such as expanded graphite (EG) [115–117] and carbon nanotube, can also be used [118,119] as the thermal conductive component and adsorbent. 3D printing technology can be used to reduce the material waste and increase the mixing of PCM and the CM [120]. Futher, the conductivity and convention coefficient need to be identified accurately. Heyhat's group developed [121] the local thermal non-equilibrium (LTNE) model using the non-Darcy law to simulate the nano-PCM melting inside the porous media. Results indicated that the porous-PCM composition reduce the temperature more quickly than the nano-PCM and the fin-PCM ones. Javani et al. [122] infused PCM in foam layers separating the LIB. When the foam is soaked in PCM and placed between the cells, the thermal management performance in terms of maximum temperature rise and temperature homogeneity is superior to that of dry foam under the same volumetric heat generation rate.

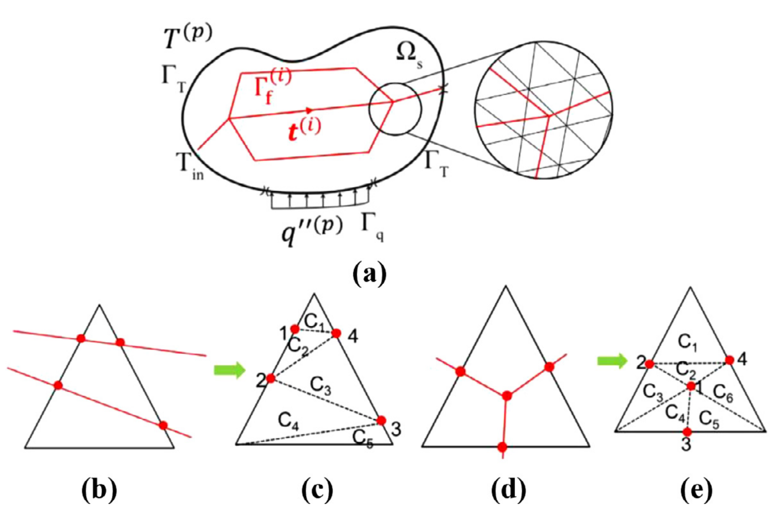

Fig. 8. Multi-objective design of microvascular panels [101].

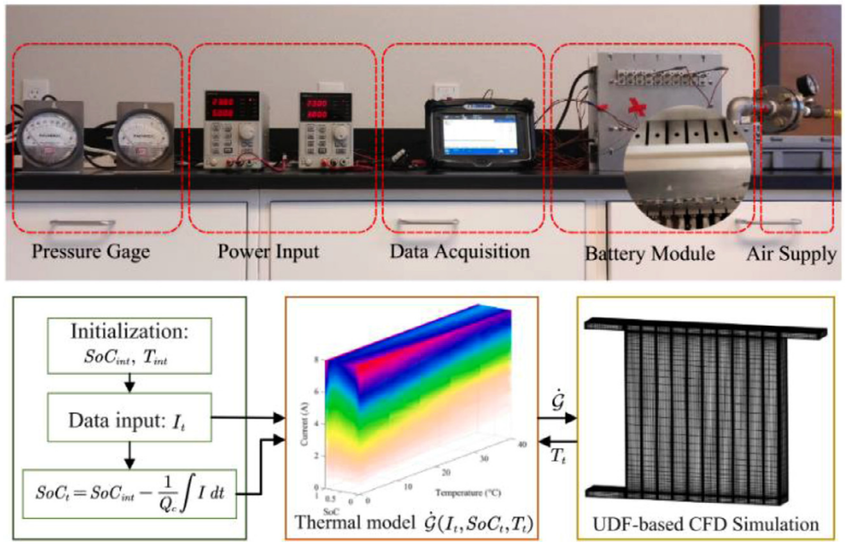

Fig. 9. The framework of the transient flow CFD model [79,105].

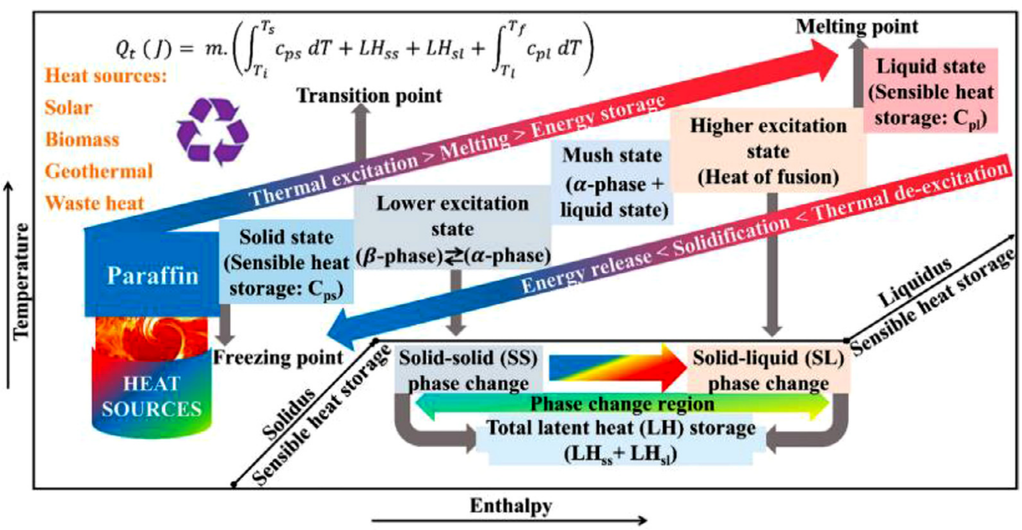

Fig. 10. Temperature characteristic of PCM based system [54].

Reducing the thermal barriers in the investigation of the structure-performance relationship is another way to optimize the PCM cooling performance [123]. Safdari et al. [124] revealed that both hexagonal and circular PCM vessels show generally the same thermal management performance and the circular PCM configuration is the best one as shown in Fig. 11. It is worth noting that the cooling effects increase very slightly when the thermal conductivity exceeds a certain range [125]. Ling et al. [107] suggested the PCM with a melting point of approximately 40 °C, a thermal conductivity above 5.4 W/m K, and a latent heat density smaller than 0.0145 kJ/m^3 should be selected. Huang et al. [126] put forward various flexible form-stable composite PCM which can lower the maximum temperature caused by thermal contact resistance. Panchal's group [127] proposed an PCM module with optimized fins and found that battery temperature is reduced by 2.38% and 9.28% at 2C and 3C current rates respectively when the optimized fins are used.

3. Multi-physical BTMS based on PCM

PCMs relies on the capacity of the latent heat to absorb heat from the cells. However, once the temperature exceeds the melting point, the cooling performance of the PCM is significantly reduced and they can act as an insulating material [128,129]. Therefore, combining cooling method with PCM to regulate the PCM temperature and thus to ensure a middle/long-term operation should be investigated. In this section, the existing solutions of PCMs in combination with other cooling media are reviewed (Table 2).

3.1. Thermal management with PCM and forced air convection

Many researchers have studied PCM system with air cooling. A secondary heat dissipation system of forced air convection [106,117,130,131] can noticeably improve the cooling performance and the temperature homogeneity. The arrangement of cells, compactness of module and thickness of PCM [84] are the main structural parameters that affect the system performance. Ling's combined system [132] successfully prevented heat accumulation and maintained the maximum temperature under 50 °C in all test cycles. Mehrabi-Kermani et al. [133] proposed a novel hybrid BTMS using PCM embedded in copper foams combined with forced-air convection (Fig. 12). The system was tested under various Reynolds numbers (Re). The results indicated that at the airspeed of 3.2 km/h, the battery temperature under high rate discharging

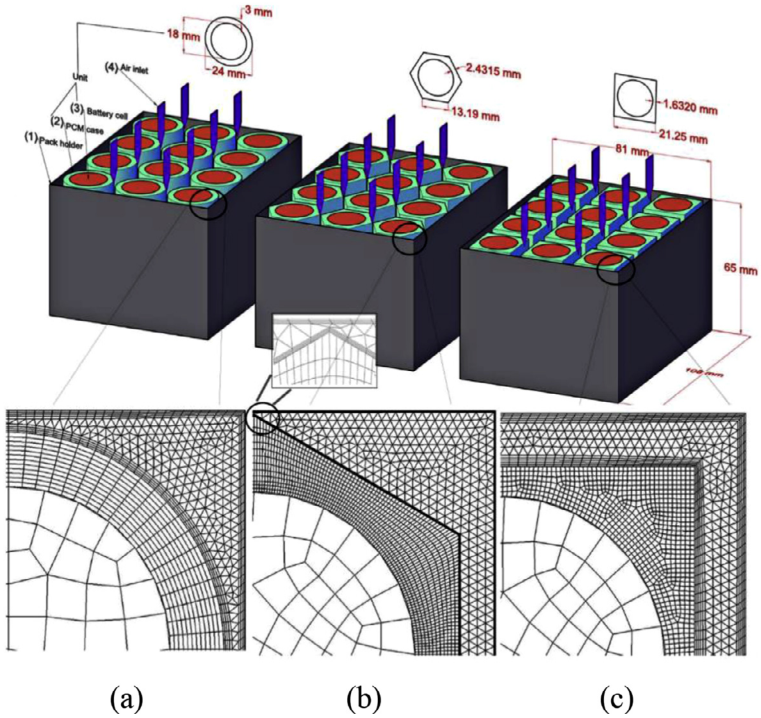

Fig. 11. Schematic of three different BTMS cases with different CELL-PCM unit shape a) circular cross section (Case 1), b) rectangular cross section (Case 2), c) hexagonal cross-section (Case 3) [124].

Table 2
Comparation of different multi-physical BTMS.

Author	PCM	Coupled cooling method	Battery positive material	Max discharge rate	Ambient temperature	Maximum temperature rise	Maximum temperature difference
He [117]	Paraffin-Expanded graphite/copper foam	Air cooling	LCO	5C	25 °C	23.0 °C	3.9 °C
Molaeimanesh [84]	Paraffin	Air cooling	LCO	3C	20 °C	13.63 °C	1.5 °C
Qin [134]	Paraffin	Air cooling	NCM	3C	20 °C	20.9 °C	3.7 °C
Huang [135]	Paraffin-Expanded graphite	Air cooling	NCM	3C	25 °C	33.24 °C	4.74 °C
Hekmat [140]	Polyethylene Glycol 1000	Liquid cooling	–	0.9C	28 °C	2 °C	0.6 °C
Kong [141]	Paraffin	Liquid cooling	NMC	3C	30 °C	11.1 °C	4 °C
Ding [142]	Paraffin	Liquid cooling	Heater	–	25 °C	16.8 °C	4.1 °C
Rangappa [143]	Paraffin	Liquid cooling	NMC	9C	–	42 °C	4.8 °C
Zhang [42]	Paraffin-Copper foam	Heat pipe cooling	LFP	5C	30 °C	18.8 °C	4 °C
Jouhara [150]	Refrigerant R404a	Heat pipe cooling	LTO	Dynamic working condition	18 °C	31 °C	2 °C
Jiang [151]	Paraffin-Expanded graphite	Heat pipe cooling	LFP	3C	25 °C	21 °C	0.8 °C
Lei [152]	Hydrated salt	Heat pipe cooling, spray cooling	LFP	1.92C	40 °C	7.9 °C	2.6 °C

is maintained below the 60 °C limit in steady state. The comparison of the hybrid BTMS with the passive and active BTMSs shows that although the active forced air convection BTMS can also keep the temperature below the safety limit at the ambient condition (24 °C), both active and passive systems were inefficient in hot weather (40 °C).

Qin developed a multi-physical BTMS which can control the maximum temperature and the temperature variance of the battery pack [134] within the optimum range under dynamic charge/discharge current loads up to 4C. Huang et al. [135] studied the influences of the design variables of the proposed BTMS, such as velocity inflow, on the thermal control performance using the Kriging-based high-dimensional model representation method which can reduce the computational expense.

3.2. Thermal management using PCM and liquid coolant

Liquid coolant have also been used in combination with the PCM [49,136,137] (Fig. 13). The thermal runway arises when the cell temperature is high, or when the cell is over-charged or under short circuit [138]. Molaeimanesh et al. [139] studied the effect of different system configuration included parallel, series-1, series-2, and parallel/series on the cooling performance of a hybrid thermal management system consisting of phase change material and

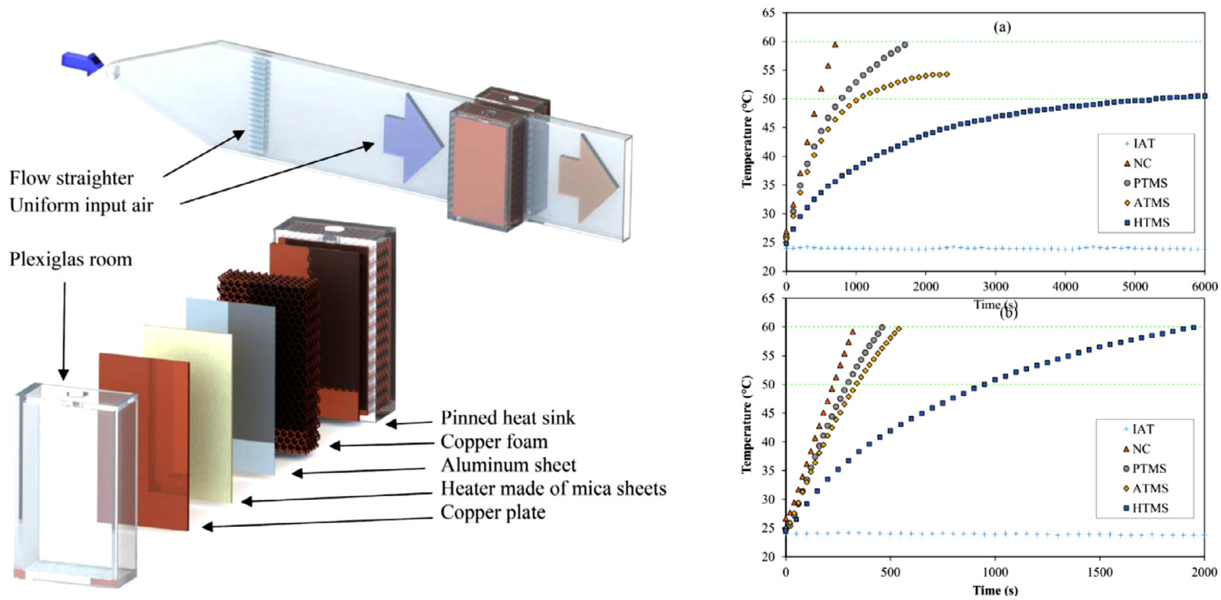

Fig. 12. Hybrid thermal management for Li-ion batteries using phase change materials embedded in copper foams combined with forced-air convection [133].

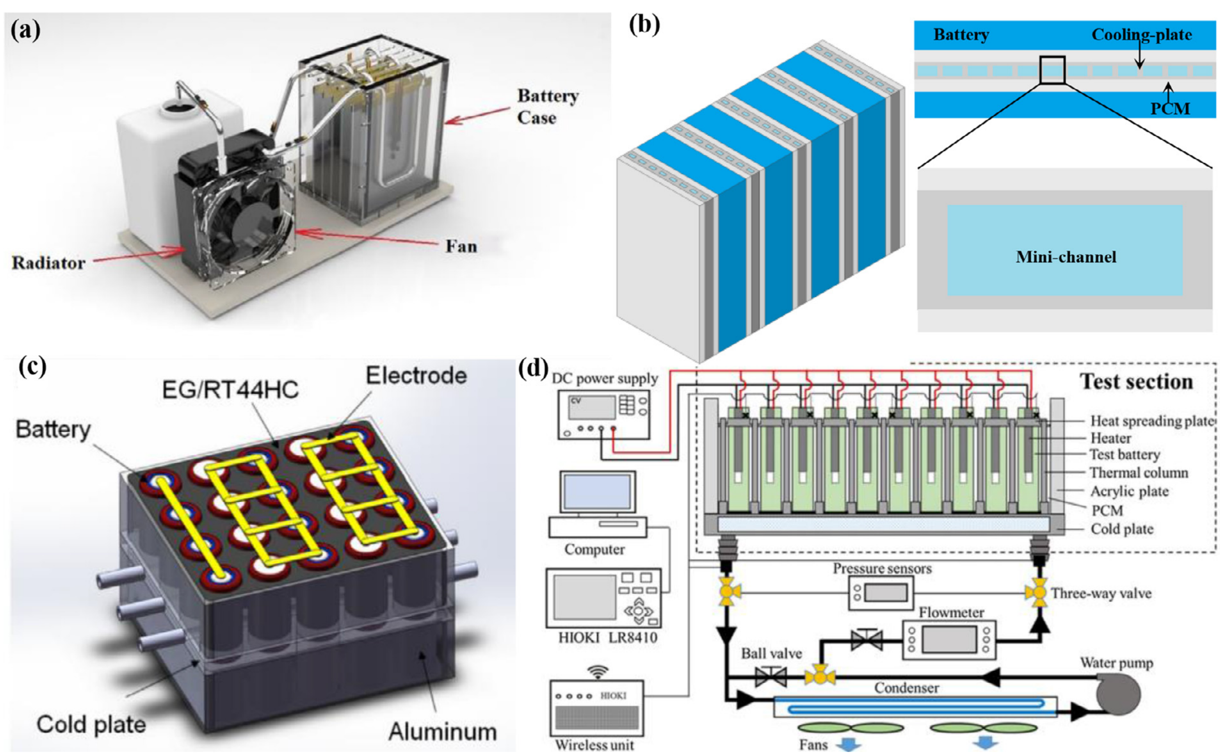

Fig. 13. Hybrid BTMS with PCM and liquid cooling.

water-cooling channels. The results show that the parallel/series configuration provides the best performance for the long period operation of the cells with a high heat dissipation rate. Water or water-ethylene glycol (1:1) mixture are commonly used as liquid coolant [116,140–143]. Novel coolants such as nanofluid [144,145] and phase change slurry [146] have also been investigated. Hekmat et al. [140] presented a multi-physical BTMS including PCM and cooling water pipes for a Li-ion module with high-capacity prismatic cells. The experimental results validated the effectiveness of the BTMS in terms of keeping a low maximum temperature rise and maintaining a uniform temperature distribution among the cells.

Cao et al. [115] designed a hybrid BTMS which integrates a cold plate through which water flows into a PCM matrix made of expanded graphite/RT44HC composites for a battery pack of 20 Li-ion cylindrical cells. The water flow control strategies were also studied. This work showed that the water temperature should be kept below 40 °C and close to the ambient temperature in order to keep the battery temperature into the proper working condition. Once the flowrate exceeds a threshold, further increase of the flowrate only reduces marginally the maximum temperature of the battery pack but will significantly raise the axial temperature and the power consumption [147]. The water cooling battery module proposed by Lv et al. [148] presented a superior cooling perfor-

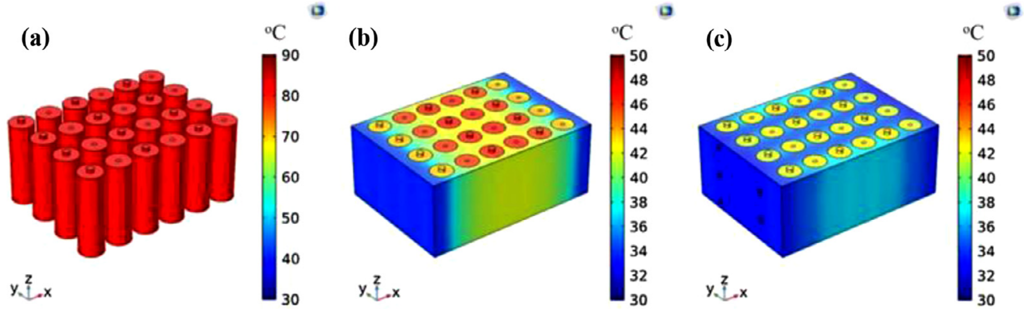

Fig. 14. Temperature contours of the battery pack with three thermal management modes [141].

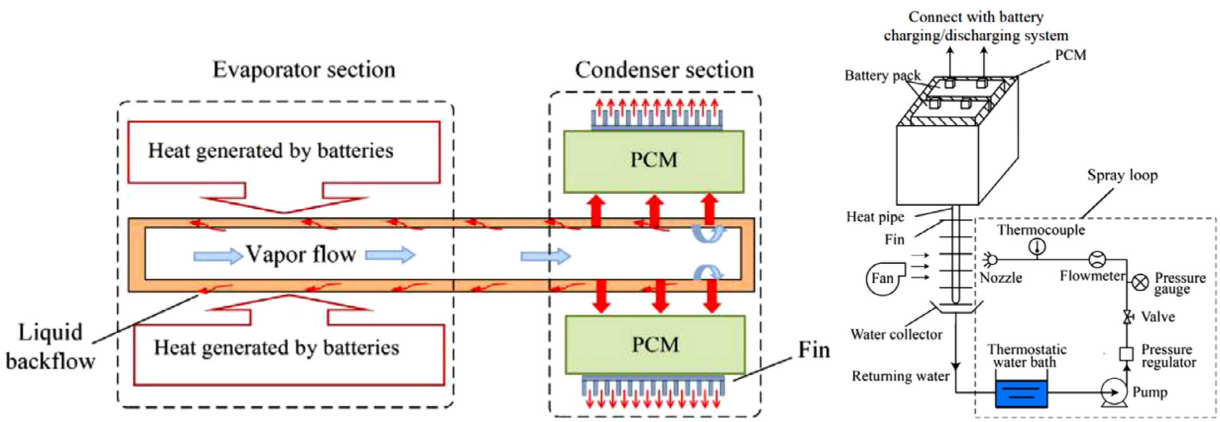

Fig. 15. The BTMS design based on PCM and heat pipe [152].

mance in terms of temperature rise and temperature uniformity: during the fast charging process at 2C and 3C, the maximum temperature of the water cooling module is 37.7 and 42.0 °C, and the maximum temperature difference is below 4 and 5 °C, respectively. Kong et al. [141] developed a coupled model of composite PCM and liquid cooling thermal management system. Simulation results showed that the BTMS exhibited good thermal performance under ambient temperature at 30 °C, which kept the maximum surface temperature and the maximum temperature difference of the battery pack at 41.1 °C and 4 °C, respectively at the end of 3C discharge (Fig. 14). Based on the system model, a liquid cooling strategy was proposed for controlling the velocity and inlet temperature of coolant by monitoring the temperature of the PCM and the environment, which further improved the thermal performance of the battery pack during cycling at different ambient temperatures and significantly reduced power consumption of liquid cooling process.

3.3. Thermal management system using PCM and heat pipes

Heat pipes have advantages such as excellent heat transfer efficiency and simple geometry. The system work on the combined effect of phase change and thermal conductivity, which can transfer heat efficiently with very small temperature drop over a substantial distance [149,150]. Jiang et al. [151] developed a lumped thermal model taking into consideration the coupling of the battery heat generation, the PCM melting and the transient thermal response of the heat pipe. The utilization of heat pipe can recover the latent heat of PCM at the end of the test cycle to ensure a low battery temperature for long-time cycling. A spray loop was added to the BTMS to ensure the cooling performance at the high ambient temperature by Lei [152] (Fig. 15). The proposed design succeeds in limiting the average surface temperature rise within 8 °C even under a high discharging current, 24 A, and a high room temperature, 40 °C. The corresponding maximum temperature difference on the battery surfaces is effectively suppressed at less than 2.6 °C.

Zhang et al. [42] developed a BTMS with PCM and heat pipe for a $LiFePO_4$ battery pack. The porous metal foam was saturated into PCM to improve the thermal conductivity. Since the filling of the PCM and other materials inside the battery pack is not required, the proposed BTMS has high safety and easy maintenance.

More novel heat pipe can also be used in the BTMS. Oscillating heat pipe (OHP) is a kind of heat pipe with low cost and high heat conductivity. However, the application of OHP will increase the height of battery module [153].

4. Emergency battery thermal barrier

LIB thermal runaways can be caused by mechanical, electrical, and thermal stress and abuse, posing a major threat to the overall safety of the battery systems [154]. The initial abnormal behavior, if not detected or extinguished immediately, can lead to subsequent massive collateral damage or even fire and explosion [47]. Therefore, it is urgent to enhance the battery safety by material optimization and emergency cooling. Three categories of EBTB are summarized as follows, the material optimization, the BMS control strategy and the fire extinguishment and heat removal.

As to the material optimization, Wang et al. [155] presented a novel concept to achieve the requisite stable and robust electrode/electrolyte interfaces by passivating a Li-ion cell and then self-heating before use. The additive, triallyl phosphate (TAP), was used in this work based on sufficient evidence in the literature of its ability to improve cell stability at both high-voltage and high-temperature conditions as shown in Fig. 16. Liu et al. [156] fabricated a novel “smart” nonwoven electrospun separator

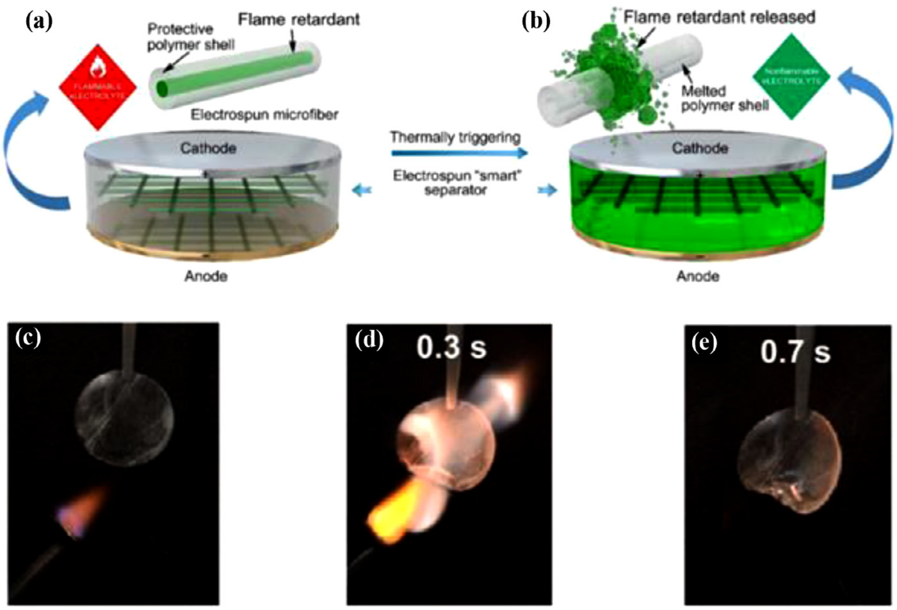

Fig. 16. Schematic of the “smart” electrospun separator with thermal-triggered flame-retardant properties for lithium-ion batteries [156].

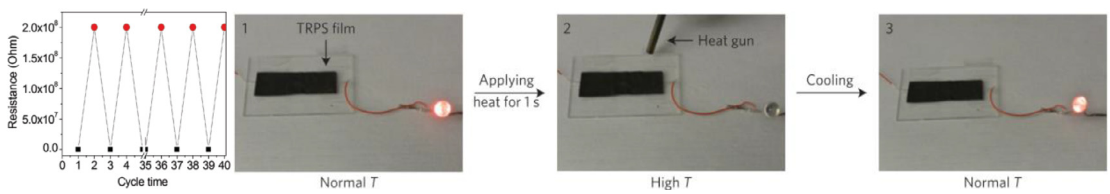

Fig. 17. Physical properties of TRPS film [157].

with thermal-triggered flame-retardant properties by adding triphenyl phosphate (TPP) for lithium-ion batteries. During thermal runaway of the lithium-ion battery, the protective polymer shell will melt, triggered by the increased temperature. The flame retardant will then be released, effectively suppressing the combustion of the highly flammable electrolytes.

Chen [157] reported a fast and reversible thermoresponsive polymer switching material that can be incorporated inside batteries to prevent thermal runaway. This material consists of electrochemically stable graphene-coated spiky nickel nanoparticles mixed in a polymer matrix with a high thermal expansion coefficient. Importantly, the conductivity decreases by seven to eight orders of magnitude within one second on reaching the transition temperature and spontaneously recovers at room temperature as shown in Fig. 17. Batteries with this self-regulating material built in the electrode can rapidly shut down under abnormal conditions such as overheating and shorting, and are able to resume their normal function without performance compromise or detrimental thermal runaway. Zhao et al. [158] reported that externally applied compression has been employed to prevent lithium ion battery failure. The results show that compression reduces capacity loss by 0.07%, 4.95% and 13.10% with the ambient temperature at 80, 90 and 100 °C for 10 h.

Emergency cooling is composed of thermal runaway monitoring and heat removal. The monitoring and detecting methods can be essentially divided into the following categories [154]:

1) Terminal voltage detection using the battery management system (BMS);
2) Battery mechanical deformation detection using creep distance sensors;
3) Internal temperature estimation by embedding optic fiber sensors in lithium-ion batteries or monitoring the battery's internal impedance change;
4) Characteristic gas component identification during the thermal runaway

Zhu et al. [16] found that the sharp drop in voltage before thermal runaway provides a feasible approach to forewarn the users of the impending risk and proposed a safety management method to mitigate the impact of overcharge and avoid the thermal runaway risk as shown in Fig. 18. When the thermal runaway is predicted to happen, some heat removal method should be used to cool the battery pack immediately [159].

After the thermal runway happens with fire and even explosion, the fire extinguishment and heat removal is necessary to reduce the property loss. Wang's group [160–162] deeply investigated the fire extinguishment of LIB and found that dry powder and water could extinguish fires and reduce the maximum surface temperature of LIB under the appreciate conditions. Meanwhile, a novel $C_6F_{12}O$ suppression and rapid water mist cooling system was constructed and tested by Wang's group [163]. Results indicated that the cell's peak temperature and high-temperature duration reduce significantly compared to $C_6F_{12}O$ only and without suppression. Gao et al. [164] proposed an open-loop emergency thermal safety management method that sprays refrigerant directly into the battery box to achieve emergency cooling, oxygen suppression, cutting off heat and combustion once the thermal runaway is about to occur. Wilke et al. [159] presented experimental nail penetration studies on a Li-ion pack for small electric vehicles, designed with and without PCC. The results show that when parallel cells short-circuit through the penetrated cell, the packs without PCC

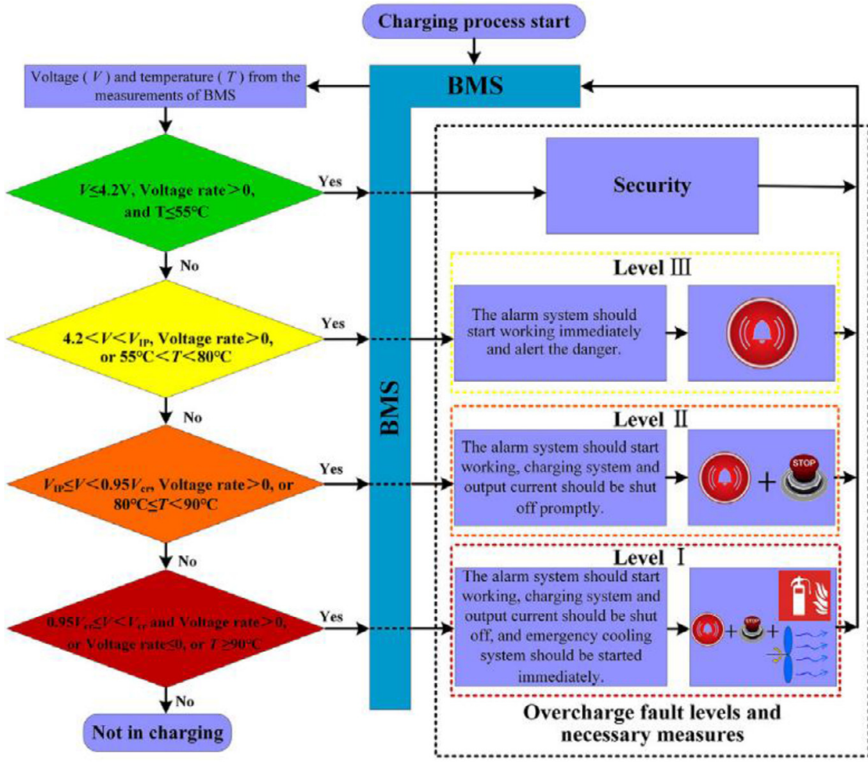

Fig. 18. The evaluation strategy of overcharge fault [16].

propagate fully while those equipped with PCC show no propagation.

5. Conclusion and future task

With the rapid development of electric vehicles, power batteries with large capacity, high energy density, and fast charging lead to the wide range of temperature distribution. Thus, batteries suffer from safety problems such as life span aging, degradation acceleration and the deterioration of stability due to an increase in the heat generation rate [47]. This paper reviews the thermal model of battery pack and classifies the cooling BTMS and EBTB. However, even though the multi-physical BTMS optimizes the cooling performance, the economic efficiency of energy consumption and lightweight design of BTMS remains challenging. Generally, multi-physical BTMS with self-adaptive intelligent control system combined with EBTB should be established to improve the temperature distribution of the battery pack as shown in Fig. 19. Precise

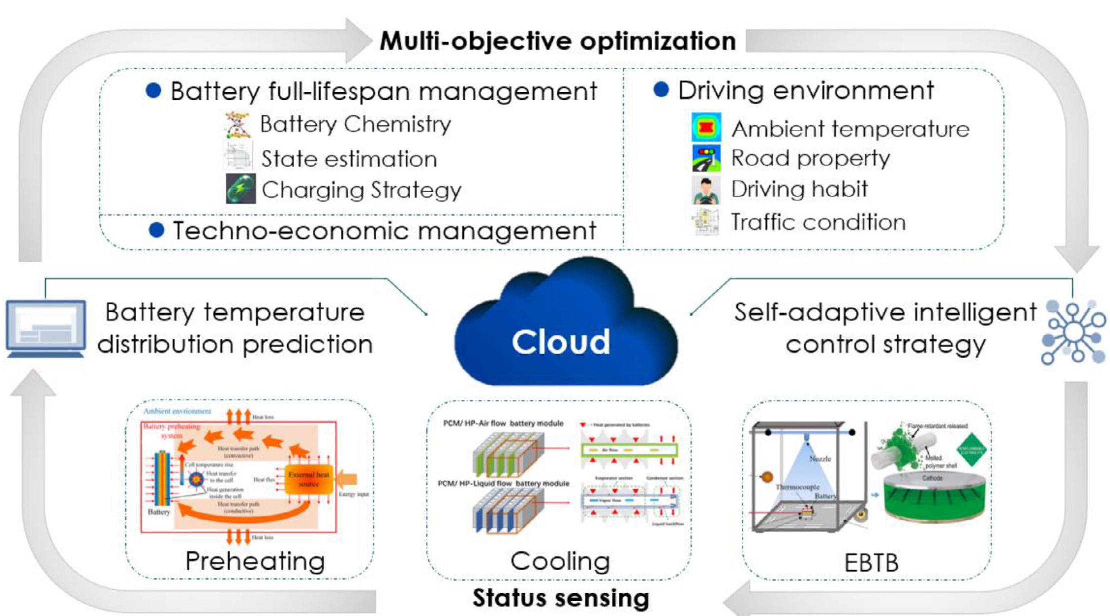

Fig. 19. A novel BTMS framework based on CHAIN.

temperature distribution prediction for power battery pack under different working conditions is the foundation of BTMS. Multi-objective optimization based on battery full-lifespan management, techno-economic management and driving environment can improve the accuracy of the temperature prediction. Battery full-lifespan management based on the detailed model should be considered. Battery chemistry including positive/negative pole, electrochemical reaction and side reaction can simulate the electro-thermal behavior of LIB at sub-cell levels. The operating states of power battery, such as state of charge (SOC), state of health (SOH), state of power (SOP) and state of energy (SOE), can be integrated into the electro-thermal model using state estimation methods. The fast charging of power battery generates lots of heat, and therefore the temperature rise model should be taken into account when designing the charging strategy. The techno-economic management, which mainly considers the ratio of useful work output by BTMS to its electric consumptions, can increase the economical efficiency of whole system. Driving environment prediction based on vehicle to everything (V2X) can effectively predict the output power of the LIB which influences the temperature rise significantly. Self-adaptive intelligent control strategy should be made to control the multi-physical BTMS including preheating system, cooling system and EBTB effectively and economically. Several emerging cooling techniques [26,165] such as thermoelectric cooling, hydrogel-based cooling, thermo-acoustic refrigeration and magnetic refrigeration emerging nowadays can offer many advantages, including significant energy and cost-saving potential along with high scalability, over traditional forced-air or liquid cooling methods. Then, the working states of the battery pack such as temperature, current and voltage are measured by sensors, which can be used to correct the temperature prediction model interactionally. To fulfill the task, data collected from the BTMS by sensors are converted to hierarchical structures by a specific methodology that involves transfer protocols and the proper data-processing methods, such as data cleaning, screening, fusion, feature extraction, and clustering, achieving hierarchical computing and control methods. Based on sensing data and fetching data from the servers, a series of desired models can be established and trained, providing guidance for battery design and the optimization process. Intelligent algorithms and communication technologies are driving the product manufacturing industry toward the big data era [166].

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.

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