

Battery warm-up methodologies at subzero temperatures for automotive applications: Recent advances and perspectives

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ABSTRACT

Electric vehicles play a crucial role in reducing fuel consumption and pollutant emissions for more sustainable transportation. Lithium-ion batteries, as the most expensive but least understood component in electric vehicles, directly affect vehicular driving range, safety, comfort, and reliability. However, the overall performance of traction batteries deteriorates significantly at low temperatures due to the reduced electrochemical reaction rate and accelerated health degradation, such as lithium plating. Without timely and effective actions, this performance degradation causes operational difficulties and safety hazards for electric vehicles. Battery warm-up/preheating is of particular importance when operating electric vehicles in cold geographical regions. To this end, this paper reviews various battery preheating strategies, including external convective and conductive preheating, as well as the latest progress in internal heating solutions. The effects of low temperature on batteries from the perspectives of cell performance as well as materials properties are briefly summarized. Thermal science issues involved in warm-up are also elucidated. The framework of battery management systems (BTMS) at low temperatures, including the key design considerations at different battery integration levels and the overall classification of warm-up approaches into external and internal groups, are introduced in detail. Next, a comprehensive literature review on different warm-up strategies is presented, and the basic principles, advantages, disadvantages, and potential improvements of each strategy are elaborated. Finally, future trends of battery warm-up methods are discussed in terms of key technologies, promising opportunities, and challenges.

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Abbreviations: AC, alternating current; ACB, all-climate battery; ACT, activation terminal; AHE, air heat exchanger; BCU, battery control unit; BEV, battery electric vehicle; BTMS, battery thermal management systems; CC, constant current; CCD, constant current discharge; CHE, coolant heat exchanger; CHM, charger module; CNT, carbon nanotubes; COP, coefficient of performance; CPCM, composite phase change material; CV, constant voltage; CVD, constant voltage discharge; DC, direct current; DC/DC, direct current to direct current; DP, dynamic programming; ECT, Electrochemical-thermal; EEC, equivalent electrical circuit; EMS, energy management strategy; EV, electric vehicle; HESS, hybrid energy storage system; HEV, hybrid electric vehicle; HVAC, heating ventilation and air condition; ICE, internal combustion engine; IGBT, insulated-gate bipolar transistors; Li-ion, Lithium-ion; LPF, lithium plating-free; SEI, solid-electrolyte interphase; MHPA, micro heat pipe array; NiMH, nickel-metal hydride; PCM, phase change materials; PCS, phase-change slurry; PHEV, plug-in hybrid electric vehicle; PTC, positive temperature coefficient; RETC, reduced electro-thermal coupled; SAC, sinusoidal alternating current; SC, supercapacitors; SHLB, self-heating lithium-ion battery; SOC, state of charge; SOH, state of health; UDDS, Urban Dynamometer Driving Schedule.

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1. Introduction

With the rapid economic and social development, there is an ever-growing need for energy resources, especially in the transportation sector. The global demand for energy will increase by nearly one-third by 2040, and oil will still dominate the transport demand [1]. Transportation electrification is a promising technology to counteract ever-rising energy demands and facilitate a sustainable energy future [2–5]. In the past two decades, various electric vehicles (EVs), such as battery electric vehicles (BEVs), hybrid electric vehicles (HEVs), and plug-in hybrid electric vehicles (PHEVs), have been developed and deployed to replace the traditional internal combustion engine (ICE) vehicles [6–9]. Traction batteries directly affect the performance, safety, and economy of these electrified passenger vehicles. However, they have technological and cost bottlenecks. Therefore, the development of traction batteries, in terms of electrode/electrolyte materials, manufacturing techniques, and system integration/controls, is critical to the large-scale deployment of electrified passenger vehicles in the future [10,11].

Lithium-ion (Li-ion) batteries, with high power and energy density, high efficiency, long cycle life, low discharge rate, and environmental friendliness [10,12], are widely adopted as the energy storage component in current electric passenger vehicles. Nevertheless, the performance of Li-ion batteries is seriously undermined by cold climates, especially at subzero temperatures. Li-ion batteries with carbonaceous anodes, which are currently the dominant type of vehicular traction batteries, are generally known for their poor performance at such temperatures, caused by reduced conductivity of electrolyte and solid-electrolyte interface (SEI) [13], slow solid-state lithium diffusion [14,15], high polarization of graphite anode [16] and increased charge-transfer resistance at the electrolyte-

electrode interface [17–19]. Internal battery resistance increases drastically at extreme conditions below -20°C , which inevitably leads to a considerable decrease in power sourcing/sinking capabilities [17]. Furthermore, there is a high risk of lithium plating at the surface of the anode when the battery is charged at extremely low temperatures, resulting in significant capacity loss and even internal short circuits once the growing lithium dendrites pierce the battery separator [20–22]. For electric passenger vehicles, the risk exists when they require charging operations in extreme weather and the battery temperature is below zero. Also, a cold start-up is typically needed after parking EV for a long period in cold weather. In such cases, the performance degradation of Li-ion batteries at low temperatures leads to a significant reduction of the driving range of electric passenger vehicles and brings potential safety hazards as well. In 2018, the global sales of EVs were nearly 2 million and the majority of them are distributed in China (1.1 million), Europe (385 thousand) and the United States (361 thousand) [23]. The inconvenience brought by frigid weather would hinder the popularity of EVs and make them less attractive in cold geographical regions such as northern China, Europe, and the United States, where the recorded average winter temperatures are often below 0°C [24]. Therefore, a big challenge for popularizing electric passenger vehicles is how to ensure normal and safe battery operations at extreme temperatures, especially below -20°C .

To address this problem, many efforts at the battery material level have been made, including the improvements in the electrolyte, anode, and cathode materials, to improve Li-ion battery performance at low temperatures to some extent [25]. Nevertheless, these improvements cannot guarantee promising overall low-temperature properties of Li-ion batteries in the short term. Other solutions can be found at the operational level, where the main-

stream methodology in the literature is to preheat batteries from extremely low temperatures to a pre-specified temperature before normal operations, especially before fast charging [26,27]. This process can be realized through BTMS in various ways, and batteries can restore the performance as soon as their temperature rises above zero. In recent years, considerable research efforts have been dedicated to developing the strategies of warming up Li-ion batteries in cold climate. Different warm-up approaches have their own merits and weakness. Therefore, the choice of appropriate preheating method is crucial to the overall performance of electric passenger vehicles at low temperatures.

Traditional battery preheating strategies typically work externally or internally, as surveyed in [28–30]. The two main strategies are (1) taking advantage of a specially designed thermal management system to transfer the heat generated by an external heat source, through a heat transfer medium that can be either solid or fluid, to the battery pack; and (2) applying a current to a battery and, due to battery internal resistance, generating internal heat to warm up the battery. Each strategy has limitations. For the first strategy, the relatively long warm-up time, high energy consumption, and low-temperature uniformity are the main concerns due to heat loss and limited heat transfer efficiency [31]. For the second strategy, current profiles that reduce the preheating time and minimize battery degradation need to be further explored [32].

Thermal management systems with higher heating efficiency have recently been investigated to address these concerns. Innovative ideas, such as incorporating more thermally conductive materials into BTMS, are likely to become promising solutions in this research area. More recently, a diversity of improved current parameters and waveforms are synthesized in internal preheating, in order to seek a delicate trade-off between heating time and concomitant battery degradation [33]. An emerging battery structure, namely, self-heating lithium-ion battery (SHLB), has provided a ground-breaking milestone for such a trade-off between preheating effect, energy consumption, and battery degradation [34].

The overarching goal of this paper is to provide a timely, comprehensive review of the latest progress in research and development of battery warm-up techniques at low temperatures for current commercial Li-ion traction batteries with graphite anodes. This work goes beyond existing relevant survey articles on thermal management [28,29]. Novel methods recently proposed, as well as a systematic classification, are explained to better reflect the technological status and development directions of this ever-evolving research field. Unlike other studies on this topic, this paper provides a summary of design considerations of BTMS at low temperatures at different battery integration levels, including cell level, module/pack level, and system level. Furthermore, a comprehensive review of various warm-up methods is presented. Various possible heating solutions for EVs in frigid weather, regardless of their technique maturity, have been extensively investigated. For external strategies, the heat transfer characteristics and heating performances are discussed in detail. Improvements on ameliorating the heat transfer rate and enhancing the heating efficiency in the external preheating systems, including the applications of nanomaterials such as nanofluids and nano-enhanced phase change materials (PCM), the adoptions of novel heating elements such as heat pumps and film-based panel heaters, are, for the first time, surveyed in the context. As for internal preheating, the latest SHLB technology and its performance improvements are presented. In addition, recent advances in alternating current (AC) heating with different current waveforms and parameters, as well as their heating effects, are also covered. Both external and internal heating strategies are discussed in terms of their strengths, weaknesses, and maturity.

The remainder of this paper is organized as follows. In Section 2, the effects of low temperature on batteries from the

perspective of materials are summarized, and the thermal science issues involved in warm-up are first elucidated. The key design considerations of BTMS at low temperatures and the overall classification for existing warm-up strategies are elaborated in Section 3. Section 4 introduces the external heating strategies, while Section 5 elucidates the internal heating strategies. The outlook and future trends are presented in Section 6, and the key conclusions are given in Section 7.

2. Key scientific issues

2.1. Low-temperature performance of Li-ion battery

It is well known that the cold climate has a significant impact on the performance of the Li-ion battery. Thus, it is important to understand the extent to which this energy storage device suffers from severe performance degradation.

A notable phenomenon of Li-ion battery at subzero temperatures is the significantly reduced discharge capacity. At -10°C , a 2.2 Ah 18650 cylindrical cell could only retain about 1.7 Ah discharge capacity at 1C discharge rate and less discharge capacity is obtained using a higher discharge rate (about 0.9 Ah in 4.6C) [35]. The decreased discharge capacity would lead to a reduction of the energy provided by the battery. A 100 Ah prismatic LiFeMnPO₄ HEV battery was tested to have an energy delivery of 226 Wh under 1C discharge at -10°C while the available energy could be 293 Wh at 25°C [36]. Besides, the cell resistance increases dramatically at subzero temperatures. According to Zhang et al., the total resistance of a LiCoO₂-based 18650 cell at -20°C could be over than $1\ \Omega$ while this value is almost less than $0.1\ \Omega$ at 20°C [17]. This drastic resistance increase will limit the power delivered by the battery. Experimental results also show that an 18650 Li-ion battery could only have 1.25% power density at -40°C compared to the obtained values at 25°C [37]. Meanwhile, charging the battery at low temperatures is likely to trigger lithium plating, which often leads to severe battery capacity fade. At -10°C , an 11.5 Ah Li-ion cell was detected to have its capacity degradation rate increasing sharply when then charge current exceeds 0.25C and capacity loss can reach even 25% after 40 cycles at a charge rate of 0.5C [21]. Higher charge rate would lead to severer capacity loss. Even at 0°C , a single charge cycle at 1C current would cause a 3.6% irreversible capacity loss of a 7.5 Ah cell [38]. Therefore, the charge rate of Li-ion battery is usually small at low temperatures in order to prevent lithium plating, which extends the charge durations dramatically.

2.2. Effects of cold climates on Li-ion batteries from a materials perspective

The performance degradation of Li-ion batteries at low temperatures is due to the changes in battery materials properties, which typically occurs on a micro-scale and makes the stored chemical energy unusable in cold weather. Such microscale changes make Li-ion batteries exhibit low charging acceptance, reduced discharge capacity, and declined power capability in a macroscale at low temperatures. Therefore, the intrinsic properties of main battery components, including anode, electrolyte, and cathode, directly affects the battery performance at temperature extremes.

The main mechanisms examined in the existing reports include [39]: 1) the interfacial phenomena in the anode, e.g., the SEI growth at a graphite anode; 2) the sluggish kinetics in the cathode, like the charge-transfer resistance increase, the inter-grain resistance increase, and the slow solid-state Li diffusion; 3) the increased electrolyte viscosity. Fig. 1 shows a variety of material factors contributing to the declined battery performance in cold weather, as summarized by Rodrigues et al. [39]. At the anode, the

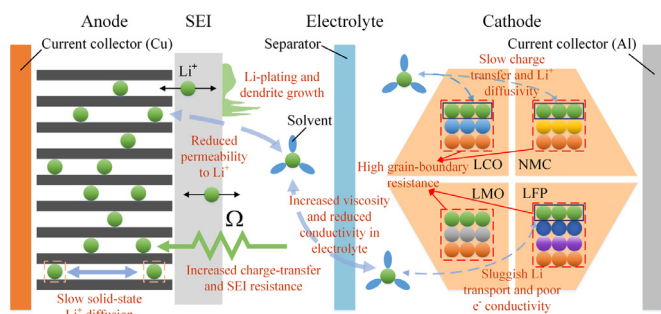


Fig. 1. Battery performance degradation mechanisms at low temperatures from a material perspective.

passivation layers at the surface of graphite, known as SEI, become less permissible to lithium ions at subzero temperatures, impeding the motion of lithium ions from the electrolyte into graphite particles. Specifically, the growing resistance contributed by charge transfer and SEI leads to a significant increase in cell impedance [18,40]. In addition, the solid-state diffusion of lithium ions descends drastically, which is more obvious in the lithiation process (charging) than in the delithiation process (discharging) [15]. All these phenomena in anode contribute to an increase in cell polarization, making the graphite anode highly susceptible to lithium plating during charging. For the cathode, the charge-transfer resistance can be more than 300% higher than that at room temperature, with much larger value at lithiated state (the discharged state) [41]. High grain-boundary resistance and slow solid-state diffusion are also regarded as intrinsic limitations. All these three factors contribute to sluggish lithium transport and poor electronic conductivity in the cathode. In terms of the electrolyte, both increased viscosity and reduced conductivity result in poor cell performance. The former factor weakens the mobility of lithium ions in the electrolyte solutions and the wettability of the electrolyte at electrodes, while the latter one accelerates the lithium-ion depletion near electrodes [40,42].

Various techniques for improving battery materials can extend the temperature frontiers of Li-ion batteries to some extent. For example, the anode using lithium titanium oxide instead of graphite or nanoparticle size; the electrolyte using organic solvents and co-solvents with low melting point and low viscosity; the cathode using doping or reduced particle size for a shorter ion diffusional path length [39]. However, commercial adoption of these enhanced materials to improve the overall cell-level performance at low temperatures constitutes a great challenge since trade-offs must be examined to balance the strengths and weaknesses of all those materials, which is difficult to achieve in a short or medium term.

2.3. Thermal science involved in battery warm-up processes

In addition to improvements of battery materials themselves, operating strategies can be used to eliminate adverse thermal effects due to cold weather, by controlling the battery temperature within a favorable temperature range. In this way, improving the battery low-temperature performance becomes a thermal issue, and researchers need to understand the thermal behavior of the battery and associated heat transfer characteristics in the cell level, module level, and pack level. To warm up a battery from a subzero temperature efficiently, the heat generation inside or outside the battery cell, heat conduction, and heat convection, etc., must be precisely modeled and controlled so that the temperature rise of the battery can be regulated well. If an external heat source exists, heat can be transferred to the battery either convectively or conductively, with some heat losses to the ambient environment on the heat transfer path.

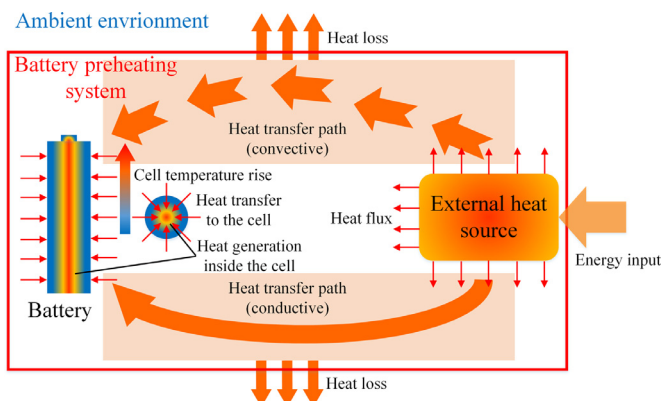


Fig. 2. Thermal issues involved in a battery warm-up process at low temperatures.

During battery warm-up, the cell geometry plays a significant role in the heat transfer from the surrounding environment to the cell interior, and thus affects the temperature distribution within the cell as well as the module/pack. Specifically, in cylindrical cells, the heat transfer process mainly occurs along the axial and radial direction. While in prismatic cells or pouch cells, the heat is usually transferred along the in-plane and through-plane direction. Besides, the thermal conductivity exhibits anisotropy in both cylindrical and prismatic cells in two directions [29], resulting in non-uniform temperature distribution within a single cell. In a battery module/pack, since the heat transfer coefficient is not the same at each position, the combination of the aforementioned factors contributes to thermal gradients inside the battery pack. Additionally, if heat generation also exists inside the battery, the battery thermal behavior (also can be affected by cell geometry [43–45]) and the heat exchange with surroundings need to be meticulously modeled in order to manage the battery temperature rise, especially for large-scale integration of batteries.

Monitoring the battery temperature during the battery heating process is also important. The temperature measurement locations are different in terms of cell geometry. For cylindrical cells, the temperature needs to be measured at different points on the cylindrical surface along the axis direction [46,47]. For prismatic cells or pouch cells, temperature measurement is required at multiple points on the two largest side surfaces [48,49]. The cell temperature is typically represented by averaging the measured temperature at different points.

Typically, operating such a preheating system requires some energy. The energy consumption needs to be considered during the warm-up process. Therefore, heat transfer paths and patterns need to be comprehensively designed to reduce undesirable heat losses, for which some improvements can be made based on theories and methodologies from thermal science. The main thermal mechanisms for battery preheating are shown in Fig. 2, in which a cylindrical battery cell is used as an example.

3. A framework of battery thermal management system

3.1. Design consideration

The goal of battery thermal management at low temperatures is to restore the energy and power capability of Li-ion batteries as well as eliminate lithium plating through heating the batteries from a subzero temperature before the operation. However, the preheating process under cold climate typically leads to extra energy consumption in EV, which makes heating batteries from low temperatures more difficult than cooling the batteries from elevated temperatures [50]. Therefore, energy optimization is needed

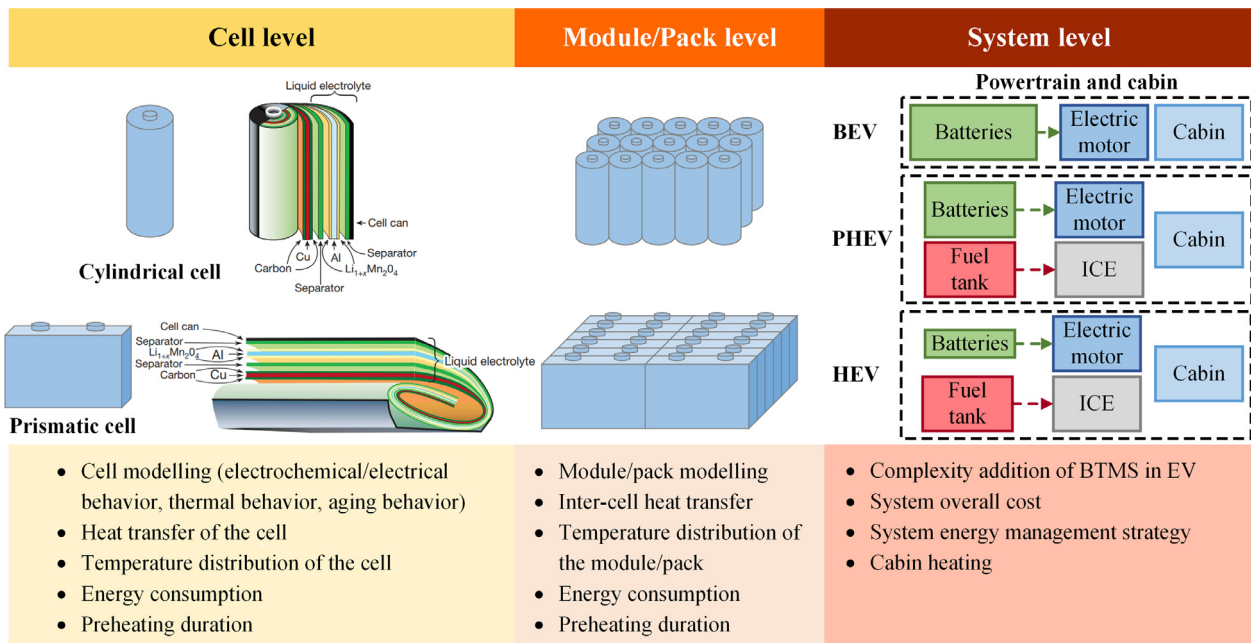


Fig. 3. Design considerations of BTMS at low temperatures at different battery integration levels. Adapted with permission from [55] (Copyright 2001 Springer Nature).

in the preheating systems in order to maximize the operating temperature range of batteries without reducing cabin comfort and depleting the stored battery energy [31]. Furthermore, the heating process cannot last too long for practical considerations, without exacerbating battery aging simultaneously. Considering this, the target temperature of preheating for the cold start-up is usually set to be above zero where batteries can restore most of their capacity and power capability. For fast charging with charge rate higher than 1C, the target temperature of warm-up needs to be much higher than 0 °C to prevent lithium plating under such a high current rate. In addition, temperature uniformity after the warm-up process plays a significant role in the performance of the batteries in both the cell level and module/pack level. For a battery cell, the uneven temperature distribution within the cell will cause local deterioration which results in battery performance degradation and life span reduction [29]. For a battery system, unbalanced charging and discharging will very likely cause temperature differences between cells and modules, which will further result in different cell aging rates and reduced overall capacity of the pack [51,52]. Therefore, preheating strategies are expected to warm up the batteries uniformly in a module/pack, with temperature difference among cells as well as modules less than 5 °C after the heating process. Other factors, such as the overall cost, system complexity addition, safety, and reliability, should also be considered when designing BTMS at low temperatures. The aforementioned design factors are listed below [28,29]:

- The electrical energy consumption;
- The preheating duration;
- The effect of heating on battery aging;
- The temperature uniformity of the battery cell, module, and pack;
- The overall cost including the cost for the system, operational cost, and maintenance cost;
- The complexity addition, such as the extra devices, weight, and space needed due to the integration of the heating system;
- The safety and reliability of the heating system.

in which (a)-(d) are treated as the performance metrics of various preheating strategies in this review while (e)-(g) are only regarded as extra consideration of the BTMS at low temperatures.

Normally, the performance of Li-ion batteries at low temperatures is decided by the intrinsic material properties. However, material improvements (including electrode modification, novel materials for electrodes and electrolyte) are long-term issues in the development of Li-ion batteries. Thermal management operation is demonstrated to be an effective measure to improve the low-temperature performance of Li-ion batteries. Since the battery system in EV consists of batteries at different levels, including the cell level, module/pack level, and system level, considerations at each level are usually different with particular focuses when designing the battery preheating systems, as shown in Fig. 3. At the cell level, it is critical to model the cell behavior precisely at low temperatures since acquiring the cell electrical potential, internal heat generation, and aging characteristics accurately are essential to the development of effective thermal management strategies. Besides, heat transfer between the cell and surrounding environment should be considered with regard to the cell geometry when designing the heat transfer path. Temperature distribution inside the cell, which is affected by the anisotropic heat transfer and different cell geometry, can become more uneven in large-format Li-ion automotive batteries. Additionally, energy consumption and heating time should also be taken into account. For module/pack level, accurate modeling of the battery module/pack is important to obtaining the heat generation, the energy and power capability of the whole module/pack in cold climate. Unlike the heat transfer of a single cell, the heat transfer in a battery module/pack is the combination of cell-to-cell interaction and module/pack-to-surrounding interaction, which could be affected by the cell geometry as well as the cell configuration inside the module/pack. The uneven temperature distribution inside the module/pack, which could trigger cell-to-cell temperature and voltage inconsistency, varies with the heat transfer and cell configuration of the module/pack. When batteries are integrated into a large-scale energy storage component in EV, the increased complexity of the low-temperature thermal management system in EV needs to be considered. Besides, the heating operations using battery power, including heating the powertrain

and cabin, are expected to have minimized cost. To this end, exploring effective energy management strategies at the system level is critical in order to achieve cost-effective heating operations, and these control strategies would vary with different powertrain hybridization and electrification extent. In addition, system heating strategies should not be at the expense of sacrificing cabin comfort of electric passenger vehicles in cold climate.

Despite that the low-temperature operations of battery systems are emphasized in this paper, the cooling operations of batteries from elevated temperatures are also critical to the performance of EV. At high temperatures, Li-ion batteries are susceptible to accelerated components decomposition and a series of side reactions, which inevitably exacerbate the battery degradation process and increase the risk of thermal runaway [53,54]. As such, the design and addition of the battery preheating system should not affect battery cooling performance at elevated temperatures to ensure that the same BTMS performs the cooling and heating role efficiently in all climate.

3.2. Classification of battery warm-up strategies

Many battery preheating strategies have been proposed in the past two decades, and the mainstream approaches are briefly reviewed in [29,31,56]. This section gives an overview of the existing preheating techniques and a widely used classification to reveal the relationships between such strategies and their common characteristics, which may help readers better understand the state of the art of this research domain.

Several typical battery preheating techniques were first introduced by Pesaran et al. [57,58]. In their work, two criteria for preheating batteries, namely the source of the energy/heat and the energy/heat transfer patterns during heating, were identified and could be treated as the classification standards for existing approaches. The classification based on these two criteria is shown in Fig. 4. According to criterion (a), the heating strategies could be divided into three groups: (1) engine heat-based heating by using fluid (air or liquid) as the heat transfer medium; (2) battery energy-based heating, in which the energy comes from the battery itself; (3) generator/inverter electricity based heating, which requires additional hardware. According to criterion (b), those strategies could be categorized into only two groups in terms of their heat transfer pattern and whether the batteries are heated externally or internally. Various heating approaches exist in each group.

The two criteria mentioned earlier are applied to different preheating strategies. Current literature tends to focus on the heat transfer characteristics of the preheating process and thus divide

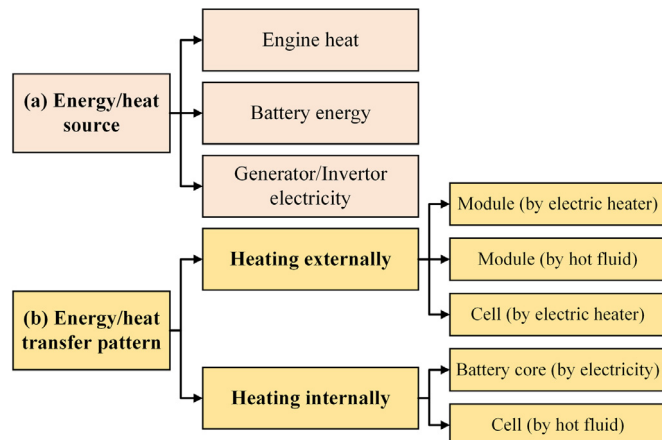


Fig. 4. Classification of preheating strategies based on two criteria: (a) the energy/heat source, and (b) the energy/heat transfer pattern during preheating.

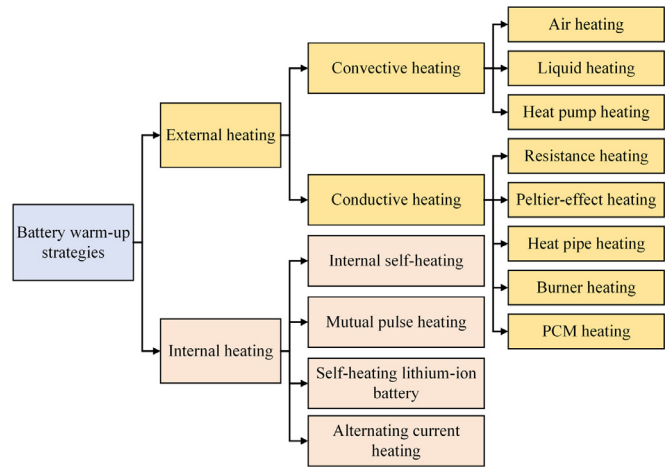


Fig. 5. Classification of existing preheating strategies based on the location of heat generation.

the heating approaches into external heating and internal heating [31,59]. However, the words “external” and “internal” were not defined before Wang et al. [31], who regarded the internal heating strategies as an alternative where the heat is generated from the source directly without passing the battery surface. Based on this definition, “external heating” and “internal heating” can be defined with respect to the location of heat generation, which is specified by the battery boundary.

This review uses the mainstream criterion, namely the heat transfer pattern during the preheating process, to identify recently proposed warm-up techniques. Fig. 5 shows the classification of preheating strategies and outlines the overall organization of this review article. The existing strategies are primarily grouped into external heating and internal heating. In external heating, although heat is generated outside the battery boundary, it can warm up the battery either convectively or conductively. Thus external heating strategies are characterized by the way in which the battery is directly heated. Convective heating includes air, liquid, and heat pump heating, whereas conductive heating includes resistance, Peltier-effect, heat pipes, PCM, and burner heating. In some strategies, such as heat pipes and vehicular power system heating, although fluid is also involved in the warm-up process, the battery is directly heated through heat conduction, and thus these strategies are considered conductive heating.

Internal heating is generated inside the battery, and different strategies are distinguished by the preheating circuit. Specifically, internal self-heating uses the battery and a load to form the circuit. Mutual pulse heating uses the battery and another energy reservoir to realize the charge/discharge process. SHLB does not need an external circuit component; instead, they use an artificially inserted metal foil to form the electric circuit that warms up the battery. AC heating typically makes use of the battery and an AC source to compose the circuit.

4. External heating

External heating strategies generally use a heat source outside the battery cells (e.g., an electric heater or a thermoelectric device) to generate the majority of heat used for battery warm-up. The heat is then transferred to the battery cells convectively or conductively to heat them up to a pre-specified temperature value, where the battery system can restore most of their energy and power capability to meet the mileage and power demand of EV or the batteries can be charged using high current rate without inducing lithium plating at the graphite anode. The configurations of BTMS

for external heating often vary with respect to warm-up strategies, in which the mass, geometry, and arrangement of the battery cells, the placement and the properties of the heat sources, the heat transfer characteristics from heat sources to battery cells could be very different and, thus, the preheating performance would differ from case to case.

4.1. Convective heating

Convective heating typically uses heat transfer media such as air or liquid to absorb the heat released from the heat source and takes advantage of the fluid flow to heat battery cells externally. In this type of method, an electrical heater or a thermoelectric heater is always needed, which can be powered either by batteries or external power source, to generate an adequate amount of heat for warming up the heat transfer medium and the battery cells. To reduce the uneven temperature distribution among cells within the battery pack, the heat transfer medium in the preheating system is required to be circulated as a way of balancing heat provided for each cell and increasing the convective heat transfer coefficient. As such, extra components are needed in this system to reinforce the circulation process. If air is used as the transfer medium, a fan is always required, whereas, for liquid, a pump is needed.

4.1.1. Air heating

A typical convective heating strategy using air as the heat transfer medium was proposed by Ji et al. [28] and can be further illustrated in Fig. 6. This heating system consists of battery cells, a heater, a fan, an airflow channel, and other control components. At low temperatures, the heater powered by the battery can produce a large amount of heat to heat the air in this system, and the warm air can subsequently heat the battery through convection. In this battery-powered preheating case, an additional amount of heat can be generated inside the battery owing to its internal resistance. This additional amount of heat can benefit the battery warm-up process by accelerating the cell temperature increase. Therefore, precise modeling of heat generation inside the cell and the cell-to-surrounding heat interaction is critical to the control of battery temperature in this self-powered heating scenario. Besides, when EV has access to external power sources (e.g., a charging stand)

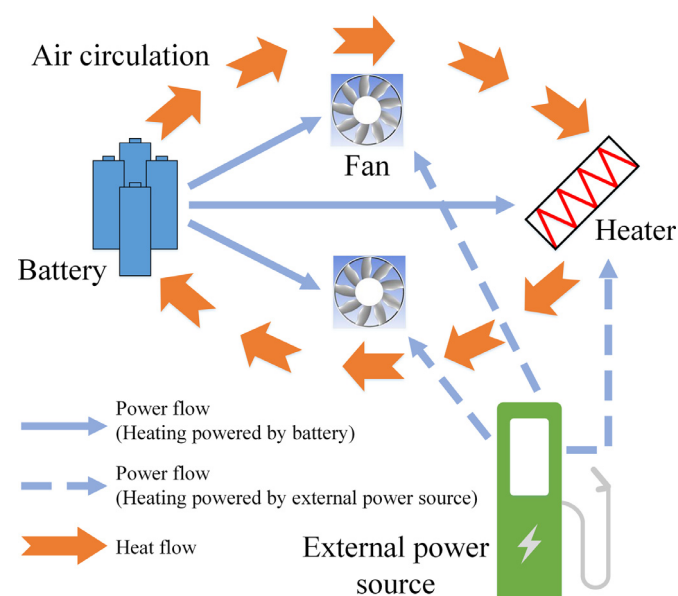


Fig. 6. Schematic of an air heating system. Adapted with permission from [28] (Copyright 2013 Elsevier).

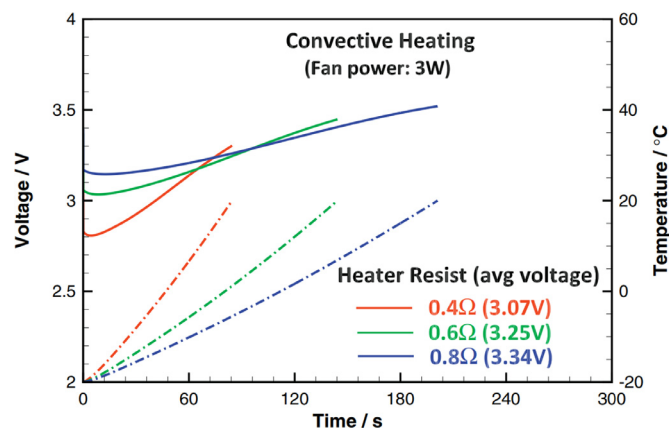


Fig. 7. Cell voltage and temperature variation during battery-powered air heating. Reproduced with permission from [28] (Copyright 2013 Elsevier).

during preheating, the fan and heater can be powered by the external power source instead of batteries. In such a case, the heat generation in this preheating system consumes grid energy rather than the battery energy so that there is no heat generated inside the battery cells, and the heating process becomes a pure heat transfer problem.

In [28], the authors established a cell-level model for the battery-powered air heating method in an enclosed space, where the boundary was assumed to be adiabatic. In their study, a single 18650 cell with 2.2 Ah was studied instead of the whole battery pack, and the heat generation inside the cell was captured by an electrochemical-thermal (ECT) coupled model. The airflow channel was designed to be along the axial direction of the cylindrical cell, and the airflow pattern was assumed to be circular-tube annulus flow between the channel wall and lateral surface of the cell. Their simulation results of this battery-powered strategy are presented in Fig. 7. There is a voltage decrease of the cell at the beginning of the heating, but with the cell temperature rise, the voltage begins to increase gradually. Using a heater with resistances of 0.8 Ω , the cell can be heated from -20°C to 20°C in 201 s. The heating time can be notably reduced to 85 s using a lower resistance heater of 0.4 Ω due to the fact that both larger voltage drop inside the cell and increased current outside the cell contribute to higher heat generation rate. However, considering the operational safety of the battery, the resistance of the heater should be carefully designed to limit the discharge rate, because the high discharge rate and the increased battery resistance at low-temperature extremes would cause the battery voltage to drop below its lower cut-off voltage at the beginning of heating, which is most likely to trigger cell over-discharge. Except for the resistance of the heater, airflow characteristic also has an impact on the heating performance. Turbulent airflow was pointed out to improve the heat transfer between the heater and air significantly, thus making the heating system more efficient.

Wang et al. [60] applied the air heating method to a battery pack. An air heating box with an inlet and an outlet was designed, in which 11 sets of resistance wires powered by an external power source are wound in parallel to heat the air. The heating box is directly connected in series to the original air cooling system so that the air flowing to the battery pack can be heated in advance. Then the warm air could be sent to the battery pack by fans to heat the low-temperature batteries. The battery pack can be heated from -15°C to 0°C in 21 min.

Song et al. [61] experimentally validated the effectiveness of air heating using an external power source. A battery, which was fully charged at room temperature, was placed in a cold environment of

–20 °C. They compared the battery remaining capacity after running 3 Urban Dynamometer Driving Schedule (UDDS) cycles with four scenarios where the preheating operations with different extents were performed in advance. Their experimental results indicated that a battery can maintain greater discharge capacity if the surrounding air is heated to room temperature level before start-up since battery internal resistance decreases when the cell is heated. The greater rated capacity also suggests a greater driving range of EV in cold climate.

For actual vehicle applications, air heating can be achieved by using control components and the heating ventilation and air condition (HVAC) system in EV to form the heating circuit. Chen et al. proposed a heating strategy by using external power [62]. The system consists of traction batteries, battery control unit (BCU), charger module (CHM), a direct current-to-direct current (DC/DC) converter, a positive temperature coefficient (PTC) heater in the HVAC system, a host-positive relay, and a host-negative relay. At low temperatures, when EV is connected to the charging pile, the CHM outside the battery pack can supply power to the PTC heater. A fuzzy controller was designed to restrict the maximum charging power of CHM to avoid exacerbated battery aging. The batteries can be then warmed up to a chargeable temperature by the HVAC system through ventilating warm air to the pack.

In the battery preheating system, heating efficiency plays a crucial role in determining the heating performance. Higher heating efficiency denotes potentially less energy consumption, shorter preheating duration, and lower system operational cost during the warm-up process. To evaluate the instant heating efficiency of the preheating system, the percentage of the consumed power used for the warm-up process is calculated. For battery-powered heating systems, the heating efficiency can be obtained using the formula below [28]:

$$\eta = \frac{c_{pC} m_C dT_C / dt}{\dot{q}_C + P_{out}} \quad (1)$$

where c_{pC} is the specific heat of the cell, m_C is the mass of the cell, T_C is the cell temperature, t is the time, the denominator represents the consumed battery power (\dot{q}_C is the internal heat generation rate of the cell, and P_{out} is the output power of the cell). When the heating elements in BTMS are powered by the external power source such as a charging stand, the heating efficiency can

be calculated as follows:

$$\eta = \frac{c_{pC} m_C dT_C / dt}{P_{in}} \quad (2)$$

in which P_{in} represents the input power to the battery heating system from the external power source.

The air heating system can be treated as a warm-up module integrated into vehicle powertrain to change the energy management strategy (EMS) of EV in a cost-optimal way and comprehensively improve vehicle performance at low temperatures. In EMS, system operating cost typically consists of battery degradation cost, electricity cost (only in BEVs and PHEV) and fuel cost (only in HEV and PHEV), which are calculated as equivalent economic cost in several driving cycles considering the cost of replacing the battery pack, charging the battery using grid electricity and the fuel consumption. Exacerbated battery degradation in cold weather would inevitably increase the EV operating cost since the cost of battery replacement in EV is usually expensive and, thus, preheating the battery before operation becomes beneficial to the cost reduction of EV. Song et al. [63] analyzed the possible benefits which could be brought from battery heating operation in a hybrid energy storage system (HESS) of BEVs at low temperatures. The HESS consists of batteries and supercapacitors (SC). The configuration of HESS with the air heating module is schematically shown in Fig. 8(a), with the average heating efficiency of 75%. An online EMS for the HESS was proposed and the minimum system operating cost (the sum of electricity and battery degradation costs) could be obtained by applying the dynamic programming (DP) approach. They found that heating the battery pack before vehicle operation can decrease the system operational cost by up to 12.49% when the battery price is 400 \$/KWh and a more remarkable cost reduction could be achieved if the battery price is higher. Meanwhile, they pointed out that the reduction of system operational costs brought by battery-powered heating operations is trivial but this benefit becomes more significant if the preheating process can be powered by an external source such as a charger. This is due to the fact that only a small heating power is required for maintaining battery temperature once the battery has been warmed up. In PHEVs, to calculate the operating cost, battery degradation cost, electricity cost, and fuel cost need to be considered simultaneously. Wang et al. [64] surveyed the potential economic benefits of preheating battery pack in a PHEV by air heating strategy in the pow-

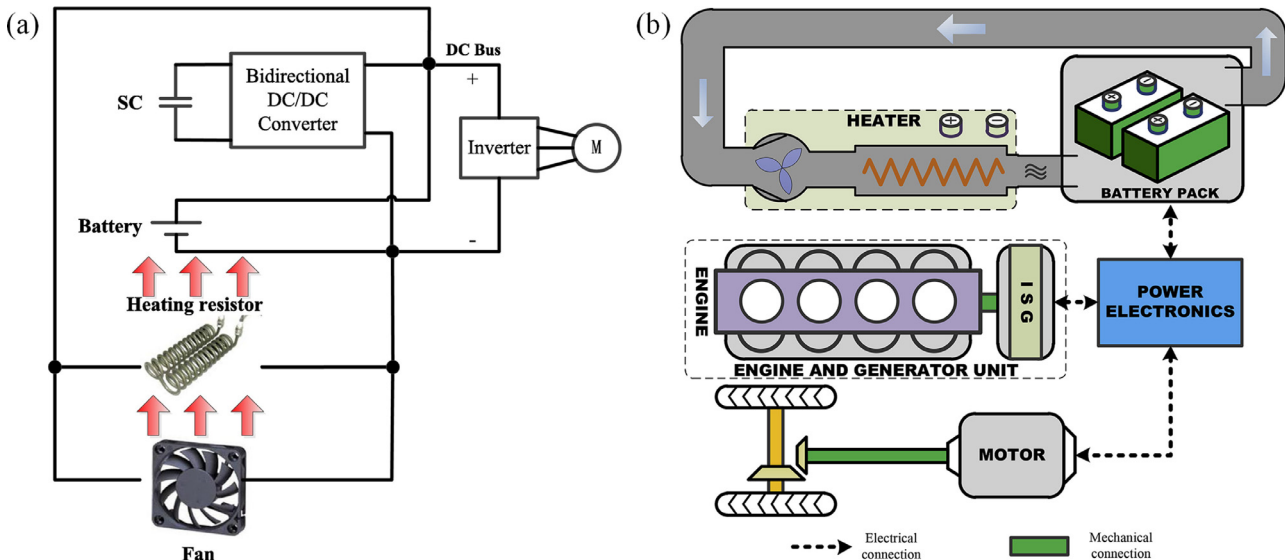


Fig. 8. Configuration of different EV powertrain incorporating air heating function: (a) hybrid energy storage system in BEV. Reproduced with permission from [63] (Copyright 2015 Elsevier). (b) power system of PHEV. Reproduced with permission from [64] (Copyright 2018 Elsevier).

ertrain, with the system configuration illustrated in Fig. 8(b). They pointed out that when the ambient temperature was -20°C , the preheating strategy could limit the operating cost by up to 22.3% in 40 driving cycles, compared to the case without a preheating process. Specifically, they also investigated the economy of preheating strategies with the choices of power from an engine and the grid with the conclusion that battery preheating powered by electricity is much more economical than using fuel.

To summarize, preheating batteries using air as the heat transfer medium presents advantages such as low system cost, small complexity addition, and high reliability, making this heating method easy to be implemented based on the original air management system. The weight increase is also small since the weight of the heater and the fan are trivial. However, the limited heat transfer coefficient of air hampers the heat transfer of the air preheating system. This makes the heating difficult for large-format automotive Li-ion batteries due to longer heat transfer distance from the cell surface to its interior, causing notable thermal gradients inside the cell. Moreover, this could also cause severe cell-to-cell temperature variation in a module/pack. The heating efficiency reported in [28] ranges between 0.6 and 0.8 throughout the heating process. However, in real applications, this actual efficiency range could be lower than 0.6–0.8 due to imperfect thermal isolation of the system, unsatisfactory electrothermal conversion of the heater, and lower-than-expected heat transfer coefficient, which results in prolonged heating duration, increased energy consumption as well as exacerbated temperature uniformity. Efforts can be made to enhance the heating efficiency by optimizing the geometric structure of the airflow channel, changing the flowing pattern of warm air (laminar flow or turbulent flow) as well as ameliorating the cell arrangement in a battery module/pack. Furthermore, considering the safety of the heating system, the current rate in battery-powered heating operation should be limited to prevent over-discharge of the battery at the beginning of warm-up. Also, the temperature of the air and heater need to be controlled below a threshold value to avoid potential fire risks.

4.1.2. Liquid heating

Compared with air, liquid exhibits a greater heat transfer coefficient so that better cell-to-cell temperature consistency could be achieved. Therefore, liquid is also widely adopted as the heat transfer medium in BTMS of EV. There are two ways that batteries can be heated with liquid, i.e., by immersing the batteries in direct contact with dielectric fluid or by placing jackets/plates containing liquid channels inside the battery pack [57]. For the latter case, the commonly used liquid includes water, oil, glycol, acetone, or mixed solution (e.g., water-glycol).

Luo et al. designed a liquid heating system for a battery pack consisting of 16 prismatic Li-ion cells with a capacity of 37 Ah [65]. The whole battery pack was immersed in a closed system filled with dielectric transformer oil. Fig. 9 illustrates the structure of the heating system. The electric heating film powered by the external power source can heat the transformer oil when the battery temperature is below 0°C . The battery pack can be heated from -30°C and -10°C to 0°C in 35 min and 12 min, respectively. Through circulating the oil in this liquid heating system, the cell-to-cell temperature difference can be controlled within 3°C . For safety concerns, the maximum temperature of the electric heating film should be far below the flashpoint of the dielectric oil to avoid the risk of fire, and the flammability of the oil needs to be considered when choosing this liquid heat transfer medium.

Compared with direct-contact liquid heating, indirect-contact heating using jacket/plate can significantly reduce the space needed for preheating systems in EV, though the walls of the heating jacket/plate might increase the thermal resistance. Yuan et al. [66] designed a battery cooling/heating jacket and sandwiched ev-

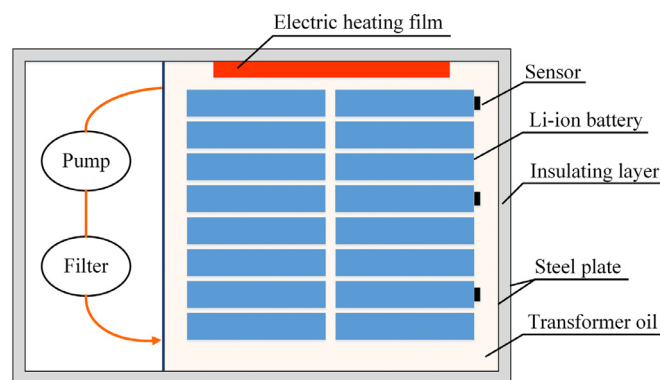


Fig. 9. Structure of an oil circulation heating system. Adapted from [65].

ery line of batteries with the two cooling/heating jackets in the pack. The heated liquid stream was contained in the jacket and flowed in a U-shaped pipe embedded in the jacket. The effects of pipe diameter, the distance of two adjacent pipes, the inlet liquid velocity, and the inlet coolant temperature were numerically investigated. These factors can be optimized to achieve more uniform and rapid heating. While the liquid flow rate and the temperature can be controlled during the preheating process, the geometry of the internal channels would determine the inherent thermal properties of the heating jacket/plate. Therefore, optimizing the configuration and geometry of liquid channels inside the heating jacket/plate can augment the heat transfer of the jacket/plate and realize uniform heating, which is beneficial to both heating and cooling processes. The improved design of the jacket/plate channel in battery cooling cases, including parallel channel [67,68], serpentine channel [69], and U-shape channel [70], can also be applied to battery warm-up in cold climates by substituting the cold coolant into the heated fluid.

Similar to air heating, liquid heating can also be mounted into EV to optimize the EMS at low temperatures. Zhu et al. [71] added three PTC heaters, which can be powered by the charging pile, to the original pipe-based liquid cooling system of a BEV. The heating liquid, a mixture of glycol and water, is in indirect contact with the battery pack and can be cycled in the loop by a pump. They analyzed the liquid heating operation in the BEV by quantifying the vehicle operating cost, which includes vehicle electricity consumption cost (consisting of preheating energy consumption, charging energy lost, vehicle running energy consumption), and battery fade cost. Their results suggest that the optimal target temperature of preheating increases when the ambient temperature becomes lower but decreases when the vehicle driving range rises since the battery can warm itself during this long-range vehicle operation. Meanwhile, the battery pack can be heated from -10°C to 2°C in 1157s, within the temperature among cells within 3.1°C .

Enhancing the thermal conductivity of the heat transfer fluid also has great significance in promoting both cooling and heating performance. At low temperatures, a highly conductive heat transfer medium enables the heat to be transferred from the heat sources to batteries more quickly and uniformly, which can efficiently improve the heating efficiency of BTMS. However, the thermal conductivity of traditional heat transfer fluid, such as mineral oil, water, and water/glycol in liquid BTMS, exhibits some limitations [54]. An effective way of improving the thermal conductivity of the heat transfer fluid in BTMS is to add thermally conducting nanoparticles into a base fluid, which could be water, ethylene glycol, or glycol-water mixture [72–75]. The application of such fluid, also called nanofluid, can further improve the cooling and heating performance of BTMS. For example, water- Al_2O_3 nanofluid with a

volume fraction of 4% was utilized by Huo et al. for the cooling of 5 cylindrical batteries connected in series [74], in which the average cell temperature can be decreased by 7% compared to pure water-based BTMS. Sefidan et al. [76] submerged each 18650 cell in the battery pack into a thin cylindrical tank containing water- Al_2O_3 nanofluid and observed improved temperature uniformity of the pack. Besides Al_2O_3 , carbon nanotubes (CNT), with high thermal conductivity, large specific surface area, and low specific gravity, can also be added to the base fluid to enhance the thermal conductivity of the nanofluid in BTMS [77]. Other nanofluids containing metallic (Cu) nanoparticles, metallic oxide (CuO , TiO_2), and nonmetallic oxide (SiO_2) can also be seen in the current literature [78–82]. The application of these nanofluids in BTMS is limited so far, but the mature technologies in other areas such as engine cooling using nanofluids may give some reference to the thermal management of automotive batteries. Other properties of the liquid, such as viscosity, density, and specific heat capacity, could also affect the heat transfer rate between the wall of the battery module and heat transfer fluid. Viscous fluid, such as mineral oil, tends to have a lower flow rate during the circulation in a BTMS under a certain pumping power [83]. Therefore, it is likely to have a thicker boundary layer compared with less viscous fluid (e.g. water/glycol) flowing with a higher flow rate, leading to a lower heat transfer coefficient, especially in a narrow channel.

To summarize, liquid has better thermal conductivity and a higher convective heat transfer rate. Both oil and water have nearly three times larger heat transfer coefficients than air [83]. Thus the nanofluid would be much more thermally conductive compared to air. As such, the liquid-based preheating system is able to achieve better temperature uniformity in the battery pack, with cell temperature inconsistency around 3 °C even using conventional heat transfer fluid. Therefore, for the warm-up of large-format Li-ion batteries, heating with liquid is more suitable than heating with air due to the superior thermal attributes of liquid. Weaknesses of liquid heating strategies also exist. Larger specific heat capacity of liquid requires more energy to warm up the heat transfer fluid at the beginning of heating, and this would probably drain the battery energy in a battery-powered heating situation in cold climates. Compared with air, liquid has much larger density, and thus, adding too much liquid in BTMS would bring much weight increase, especially in the direct-contact liquid heating case. In addition, liquid heating systems need careful (and therefore complex) seal design and operation, e.g., to avoid leakage, in contrast to air counterparts, which inevitably increases the number of control units as well as the system complexity. Despite this, the liquid management system is still widely adopted in commercial EVs with high safety and reliability due to its technical maturity.

4.1.3. Heat pump heating

A heat pump is a device that can achieve efficient heating through the reversed Carnot cycle. It absorbs heat from the surrounding environment and releases it to the area to be heated. The coefficient of performance (COP) of the heat pump is defined as the ratio of the amount of heat provided to the required work. The COP is typically greater than 1, which means that heat pumps consume less energy than electric heaters when providing the same amount of heat. Therefore, the application of heat pumps in thermal management systems of EVs may reduce the battery energy consumption for cabin heating and battery warm-up in cold climate. Recently, Bosch used heat pumps in EV to capture the waste heat from electric motors and power electronics, and use it to warm up the vehicle cabin and keep the battery at around 35 °C, which can extend the vehicle driving range by 25% [84]. Lee et al. applied a heat pump in an electric bus to capture the waste heat generated by electric devices and reuse it to heat the bus cabin [85]. Results showed that the COP value of the heat pump can

reach 2.4 when the ambient temperature was 10 °C. However, the heat pump using a single heat source does not work efficiently under the cold condition such as −10 °C ambient temperature, and the COP value is close to 1 (at 0 °C, the COP value could range between 2 and 3 for a heat pump with single heat source) [86], which means heat pumps become less advantageous compared to electric heaters. The heating performance can be improved by utilizing the heat from multiple heat sources such as air and waste heat in EV, and the COP value could be increased to higher than 2 at −10 °C [86].

To summarize, heat pumps can typically achieve higher heating efficiency than electric heaters with high safety and reliability when the same amount of battery energy is consumed. However, the low-temperature extreme poses challenges to the heating performance of heat pumps, which requires the investigation and improvement of heat pump heating technology at extremely low temperatures such as −20 °C [87]. Besides, the addition of condenser, evaporator, compressor, refrigerant, as well as plenty of control components to EV, would significantly increase the cost, weight, and complexity of this heating system. Despite the relatively mature technology of heat pumps in the integrated thermal management of EV, their applications in warming up batteries have seldom been investigated.

4.2. Conductive heating

In conductive heating, the heat-source elements are placed in direct contact with Li-ion cells or modules. Therefore, the heat generated by the heating elements can be conducted to battery cells and warm them up directly, reducing the amount of heat loss on the heat transfer path. Conductive heating mainly includes resistance heating, Peltier-effect heating, heat pipes, burner heating, and PCM heating.

4.2.1. Resistance heating

By placing the electric heaters or heating plates containing electric heating wires at the surface of battery cells, the heat produced by the heater can be transferred to the cells in a straightforward manner with significantly reduced heat transfer distance compared to convective heating and, thus, the heat loss to the ambient environment can be accordingly reduced. The most commonly applied electric heaters in BTMS include PTC heater and metal resistance (MR) heater, which could be powered by either the battery or external power source.

PTC material is a temperature-sensitive semiconducting resistive material. The resistance of PTC heater increases significantly when its temperature exceeds the designed temperature threshold so that the current flowing through the PTC heater can be regulated by itself, and the temperature of the heater can be maintained to a certain level [88,89]. Therefore, using PTC heaters with an appropriate temperature threshold to heat battery cells can prevent battery cells from overheating. Typically, PTC resistance wires are inserted into or twined around the aluminum plates, and these plates are placed between every adjacent cell pairs in a prismatic battery pack. The heat generated by inserted PTC wires can be distributed evenly on the aluminum plate due to the plate conduction and then warms up the adjacent battery cells uniformly from low temperatures. For example, a battery module (consisting of 3 LiMn_2O_4 prismatic battery cells with a nominal capacity of 35 Ah for each cell and sandwiched by 4 aluminum heating plates) can be heated from −40 °C to 0 °C in 25 min, when PTC heaters were under an external power source delivering the heating power of 35 W [90]. PTC heating can also be powered by the battery itself, and in this battery-powered heating case, the heat generated inside the battery cells and the energy consumption of warm-up should be considered. A schematic diagram of

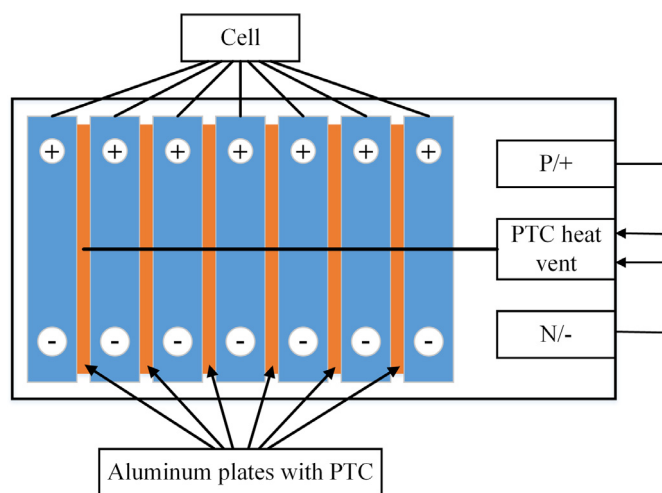


Fig. 10. Schematic diagram of a battery-powered positive temperature coefficient heating system. Adapted with permission from [91] (Copyright 2016 Elsevier).

the battery-powered PTC heating at the pack level is shown in Fig. 10. The aluminum plates with embedded PTC resistance were also placed between adjacent cell pairs. Jin et al. conducted experiments on this battery-powered PTC heating in a prismatic battery pack [91,92]. Results show that when the pack is at 100% initial state of charge (SOC), the batteries can be heated from -19.3°C to -2.4°C in 48 min, with temperature difference among cells less than 3.506°C . This battery-powered heating process consumes approximately 13% of the total pack energy. Besides, the pack with lower initial SOC value was observed to have longer preheating duration [92].

Besides PTC, MR materials are also adopted as heat generation elements in electric heaters. Wide-line metal film, which adopts copper wire to generate heat, can also be applied in BTMS to heat the batteries [93]. Similar to PTC heating, by placing wide-line metal films on the two largest surfaces of prismatic battery cells, a battery pack could be heated. Experimental results show that under 90 W heating power, the battery pack can be heated from -40°C to restore 80% of the room-temperature discharge capacity in 15 min [93].

The placement of the electric heater in a battery pack also has an impact on heating performance due to the geometric effect of cells. Zhang et al. [94] compared the case of placing heaters at the side surface of prismatic battery cells with the case of placing the heater at the bottom of a battery pack. With the same energy consumption, the side-heating method enabled a battery system to have a higher temperature rise and better temperature uniformity compared to the bottom-heating method.

In resistance heating, the heating effect also relies on the properties of the electric heater. Factors such as heat capacity, electro-thermal response, electro-thermal conversion capability, and temperature distribution during heating, can affect the heating performance of the electric heater. Film-based panel heaters, which are developed based on CNT, exhibit low weight, low thermal capacity, uniform heating, and quick electro-thermal response time [95]. Therefore, with these attributes, film-based heaters have great potentials in reducing energy consumption and heating time during battery warm-up. Besides, compared with those relatively bulky conventional electric heaters, the small thickness of these film-based heaters enables a reduction of installation space in a battery pack. Generally, film-based heaters with high heating performance can be classified into several categories: (a) Pure CNT-based heaters, including single-walled [96,97], double-walled [98,99], and multi-walled [100,101]; (b) Metallic nanowire-based heaters

[102,103]; (c) Composite film heaters which combine CNT with organic materials [104], metallic nanowires [104], or particles [105]. These film-based panel heaters usually present better heating performance than traditional heaters under a relatively low voltage excitation. Therefore, the technology maturity of these film-based panel heaters may give rise to their applications in battery thermal management in cold weather so that the heating efficiency can be improved without adding too much complexity (control components needed and extra weight or space addition) to BTMS.

To sum up, the straightforward heat conduction of resistance heating enables a shorter heat transfer route and reduced heat loss to the ambient environment. Hence, high heating efficiency, short heating time, and low energy consumption can be achieved. However, this preheating strategy also exhibits limitations. First, the application of this warm-up technique is highly dependent on the geometry of battery cells. For prismatic batteries, the flat and large side surfaces guarantee good contact between the electric heating panel and the cell in a module/pack. However, for the cylindrical battery, the cell geometry does not allow perfect contact between the cell surface and the heater, which inevitably reduces the effective heating area and limits the heating efficiency. Therefore, resistance heating is more preferable in a battery module/pack consisting of prismatic cells. In addition, for large-format Li-ion batteries, increased cell thickness renders larger temperature gradients in a cell due to massive and quick heat accumulation at the surface of the cells as well as prolonged heat conduction from the cell surface to the core. Moreover, massive integration of cells in a battery pack typically requires plenty of electric heaters, and the installation of these heaters could take up some space and add much weight, especially when these heaters are relatively bulky. Since resistance heating is a direct-contact heating method, for safety concerns, the power of heating and the temperature of the heaters have to be limited to prevent the local overheating within the battery module/pack.

4.2.2. Peltier-effect heating

The Peltier effect describes a heating/cooling phenomenon at the interface between two different conductors when current flows through them. The direction of the heat flow can be switched by changing the direction of the current [106]. Peltier effect-based devices have been designed and applied to thermal management of EV with high reliability and lightweight [107–110]. Alaoui et al. [108,110] presented a thermal management system based on Peltier-effect thermoelectric devices to warm up automotive batteries at low temperatures. The basic thermal management unit in the system is shown in Fig. 11(a), consisting of 12 Peltier-effect units sandwiched between two heat sinks. Three similar units were designed for the thermal management of the front battery compartment, the rear battery compartment, and the passenger compartment, as shown in Fig. 11(b). The temperature in the thermal management system could be regulated by a thermoelectric controller by adjusting the current flowing through the unit. A hose system can distribute the heated air to different compartments. The placement of thermal units in the vehicle is shown in Fig. 11(c). Experimental results indicate that the front battery compartment and the rear battery compartment can be heated from 17°C to 37°C and 29°C within 20 min, respectively. The temperature difference between the front battery compartment and the rear battery compartment is due to heat dissipation from the hose system to the ambient. Besides, this warm-up process consumed 2.5% initial capacity of the battery pack.

The Peltier effect-based device can also be applied in direct contact with the battery module in BTMS to realize heating, even though in the current literature this thermal management system has been primarily used to cool the battery [111,112]. The temperature at the hot side of Peltier effect-based device can reach above

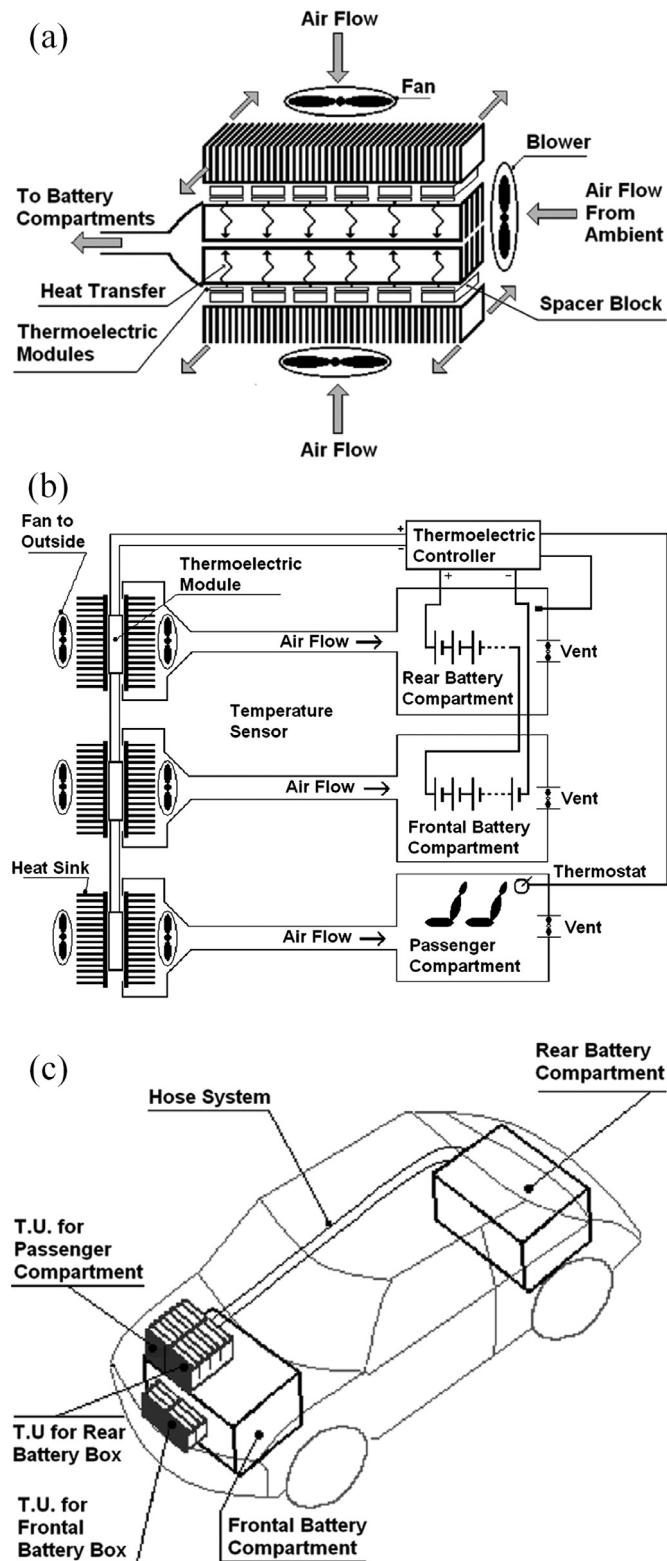


Fig. 11. Structure and distribution of the Peltier-effect thermal management system. Reproduced with permission from [108] (Copyright 2005 IEEE): (a) basic thermal management unit, (b) block diagram of the thermal management system, and (c) placement of thermal units and battery boxes in the vehicle.

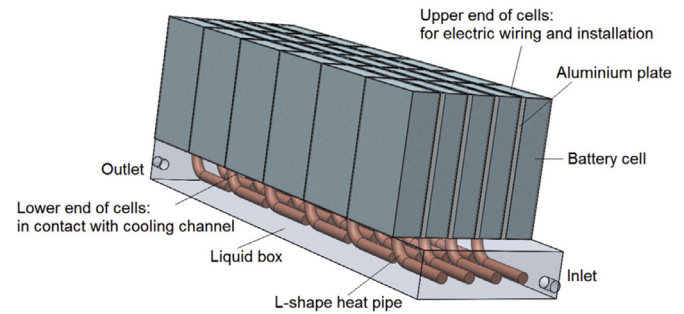


Fig. 12. Battery thermal management using copper-water heat pipes. Reproduced with permission from [113] (Copyright 2014 Elsevier).

40 °C [111] so that the same system can also be used for battery preheating at low temperatures by changing the direction of current flow.

To summarize, Peltier-effect heating can achieve battery heating safely and reliably with easy implementation of the Peltier-effect device. Nevertheless, the highest COP value reported in [108] is 1.036 when the ambient temperature is 17 °C, which suggests that the heating performance of this Peltier-effect based thermal management system is close to resistance heating (COP is approximate to 1). Therefore, the designed thermal management system in [108] may not work as efficiently as resistance heating does in cold climates, especially when the ambient temperature drops below 0 °C. This could result in increased battery energy consumption and prolonged preheating duration. Moreover, researches on heating batteries in direct contact with Peltier-effect devices are limited, and thus, further investigations are needed in the future.

4.2.3. Heat pipe heating

A heat pipe is an efficient thermal element for heat transfer that can be used in battery thermal management for both high- and low-temperature conditions. It takes advantage of evaporation and condensation of the internal fluid when circulating inside the heat pipe to transfer heat between two ends in a spontaneous way. Wang et al. [113] designed a thermal management system based on heat pipes to realize both cooling and heating functions, as shown in Fig. 12. L-shaped heat pipes were inserted into the cavity between adjacent pairs of battery cells, with one end each attached to an aluminum plate. A liquid box with an inlet and an outlet was placed underneath the battery module, in which the other end of each L-shaped heat pipe was immersed in the fluid. At low temperatures, the hot fluid flowing through the liquid box was capable of providing the heat to warm up the batteries. The heat from the hot fluid could be transferred quickly along the heat pipes and distributed uniformly on the aluminum plate so that the battery was able to be heated. Results illustrated that, by using 20 °C hot fluid, cells can be heated from −15 °C and −20 °C to 0 °C in 1200s and 1500s, respectively. While, by using 40 °C hot fluid, the cells can be heated from −15 °C and −20 °C to 0 °C in 300s and 500s, respectively.

Micro heat pipe array (MHPA), a novel heat pipe structure with high thermal conductivity, can also be applied to improve the heating performance, as shown in Fig. 13(a). Each micro heat pipe in the MHPA runs independently, and multiple pipes working simultaneously can greatly enhance heat conduction [114,115]. Ye et al. [48] applied an MHPA for battery heating at low temperatures. In the designed thermal management system, the evaporator section of the MHPA was placed at the cell surface between every two adjacent batteries, while the condenser section was exposed to air. A heating plate was placed on the evaporator section of the MHPA so that the heat could be transferred to the battery through the MHPA, as shown in Fig. 13(b). The configuration of the MHPA in a

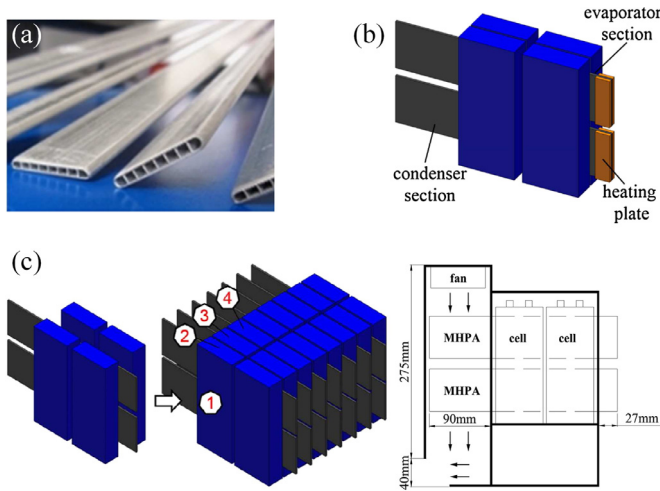


Fig. 13. MHPA in battery heating at low temperature. Reproduced with permission from [48] (Copyright 2017 John Wiley and Sons): (a) photograph of MHPAs; (b) a local structure of thermal management system; and (c) configuration of MHPA in a battery module.

battery module is displayed in Fig. 13(c), where the average temperature variation of batteries 1–4 during the preheating process was recorded to approximate the temperature of the battery mod-

ule. Under a heating power of 30 W, the battery could be heated from -10°C , -20°C , and -30°C to 0°C in approximately 350 s, 780 s, and 1100 s, respectively.

At the system level, Zou et al. [116] presented an integrated thermal management system for a five-chair EV, including a heat pipe-based subsystem for battery temperature management and a heat pump air conditioning system for cabin heating. The whole thermal management system can be used for both heating and cooling purposes of the battery as well as cabin, as shown in Fig. 14. In a preheating mode, the refrigerant valve RV1 and RV4 were closed while RV2 and RV3 were open. The expansion valves EXV2 and EXV3 could adjust the refrigerant flow rate of the cabin evaporator and battery chiller. The air heated by the heat pump can warm the cabin while the coolant heated by a PTC heater can provide heat for the battery pack through heat pipes. Experimental results showed that the COP for cabin heating could reach 1.34 when the ambient and in-car temperature was -20°C and 20°C , respectively. The battery pack could be heated from -20°C to 0°C in less than 900 s during the warm-up process.

To summarize, heat pipes, with excellent heat transfer performance, enable the heat from the heat source to be transferred quickly to batteries. Therefore, the battery warm-up time from -20°C to 0°C can be usually controlled within 15 min in the aforementioned researches. In addition, the lightweight, low cost, and mature technology of the heat pipes allow them to have great potential in battery heating with high safety and reliability. How-

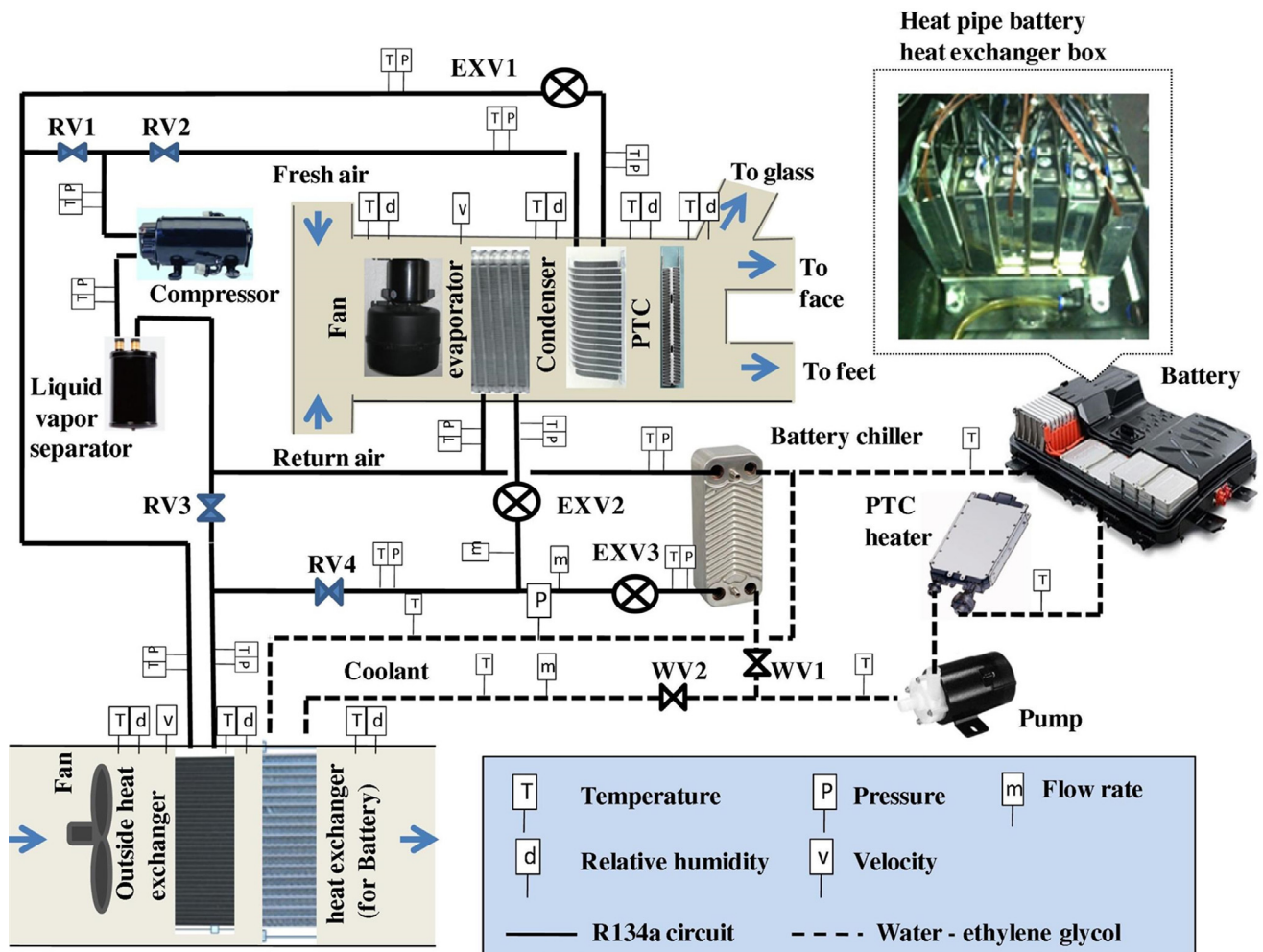


Fig. 14. Schematic of an integrated thermal management system with a heat pipe preheating sub-system for batteries. Reproduced with permission from [116] (Copyright 2016 Elsevier).

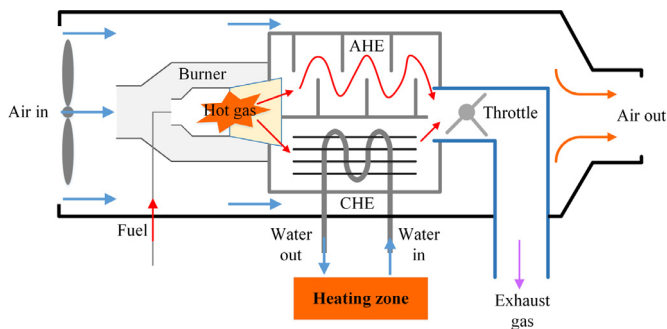


Fig. 15. A new combustion-based heating system. Adapted with permission from [117] (Copyright 2017 Elsevier).

ever, the applications of heat pipes are dependent on the cell geometry since flat cell surface could ensure better surface contact. Moreover, temperature difference may exist along the heat conduction direction of the heat pipe, especially when the heating power is high, which contributes to thermal gradients inside the battery pack.

4.2.4. Burner heating

In order to avoid the battery energy consumption during heating operations in EV, especially when cabin heating is involved, researchers have proposed some heating strategies by making use of other energy sources. Cho et al. [117] presented an integrated heating system for the thermal management of both the cabin and the battery in EV in cold climate based on a burner, as shown in Fig. 15. Fuel combustion in the burner can generate an adequate amount of heat, which could be brought out by exhaust gas. The flow controller, a variable throttle, can control the flow of the exhaust gas to the air heat exchanger (AHE), the coolant heat exchanger (CHE), or both of them. The AHE can deliver the heat from exhausted gas to the cold air in the vehicle cabin and realize cabin heating. The CHE, with its working fluid heated by hot exhaust gas, can warm up the battery pack. Later, Seo et al. [118] systematically investigated the heat transfer characteristics of this integrated heating system by considering factors such as heat exchanger effectiveness, heat transfer rate, temperature distribution, and fluid flow characteristics. Their simulation results validated the effectiveness of this heating system.

To sum up, this heating method can realize efficient cabin and battery heating without depleting the battery energy through fuel combustion in a burner. However, incorporating such an independent heating system to EV would significantly take up space and increase the cost, weight as well as complexity. Besides, the application of this heating system in BEVs is unrealistic due to the lack of fuel tank in BEVs as well as the great complexity addition. Additionally, for safety concerns, incorporating a burner in the heating system would bring potential fire risks to vehicles if the system is not well designed.

4.2.5. PCM heating

PCM can absorb and release a certain amount of heat through melting or solidifying at a specific temperature. They are essentially a thermal energy storage device, which can be used management battery temperature in BTMS. The melting process can be applied for heat absorption at elevated temperatures, while the heat released by the solidification process can be used for low-temperature heating. The cooling applications of PCM in battery systems have been reviewed in [119,120]. For low-temperature case, a PCM is able to prevent the battery temperature from dropping significantly when the ambient temperature suddenly decreases. By rejecting its latent heat to battery cells during the so-

lidification process, a battery module can be heated, and its temperature can be maintained for some time [121]. As a passive thermal management strategy, using PCM to heat batteries can eliminate the need for adding extra control components in BTMS since the solidification process is merely related to the intrinsic properties of PCM. Moreover, the phase change process of PCM does not consume battery energy so that the warm-up process can be completed without sacrificing the driving miles of EV.

The temperature-retaining capability of PCM at low temperatures was experimentally investigated by Ling et al. [122]. They found that the adopted PCM can keep the battery above 5 °C for about 1 h when it is cooled from 40 °C in a cold environment of −10 °C. They also pointed out that the thermal mass of PCM impedes the battery temperature from rising rapidly in a single discharge after a long-time soak in a cold environment. However, in continuous charge-discharge cycles, the battery with PCM has a higher average temperature than the case without PCM and thus can have better performance.

Zhang et al. [123] devised an active battery heating method based on a phase-change slurry (PCS) cycle. PCS is a microencapsulated PCM combined with a solution such as water or water-glycol, in which the PCM was chosen to have a melting temperature of 10 °C. In a PCS cycle, the PCS absorbs heat in the vehicle cabin with the PCM phase changing from solid to liquid when the cabin is heated by the air conditioner and transports it to the battery container by a pump. Then the PCS releases heat with the PCM phase changing from liquid to solid and warms up the battery, which enables the battery to work at 5–10 °C. However, this heating system is not applicable in the extremely cold environment, such as −30 °C, because of the large heating load. Huo and Rao [124] constructed a lattice Boltzmann model for battery thermal management at low temperatures based on PCM. They found that three factors help to decelerate the solidification process of PCM and preserve battery temperature in cold climates, namely lower thermal conductivity, greater latent heat, and higher environmental temperature. Nevertheless, larger latent heat was pointed out to cause more severe temperature mal-distribution within the cell, which is likely to shorten the life span of the battery.

However, the heat released from the natural solidification process of PCM can only delay battery temperature drop in a cold climate, which is effective in short-term parking cases of EV but may not be applicable in a long-term stop situation. The research of Ghadbeigi et al. shows a tradeoff between keeping the battery temperature and delaying the battery warm-up when applying PCMs to manage battery temperature in a cold environment [125]. Their results indicate that paraffin wax, with low thermal conductivity, is effective in keeping the battery module warm in a short stop (10 min) at −17 °C but could slow the battery warm-up process after a long cold stop (2 h). Paraffin-graphite composite with high thermal conductivity, however, could not even keep the battery temperature during a short stop. Therefore, the net benefits brought by the natural solidification process of PCM depend not only on the stop duration but also on the type of PCM utilized. For such passive thermal management strategies used for short term parking, choosing PCM with appropriate latent heat, melting/solidification temperature and thermal conductivity is critical to the performance of BTMS in frigid weather since the ability of PCM in keeping the battery temperature, eliminating the temperature mal-distribution and facilitating the battery temperature rise after cold stop should be balanced properly.

There are also cases where the temperatures of both battery and PCM are close to ambient temperature after a long-term stop in cold weather so that PCM no longer releases heat to keep the battery temperature. In such cases, a built-in heat source is required to provide adequate heat for the cold start-up of EV. During this warm-up process, PCM acts as a heat transfer medium

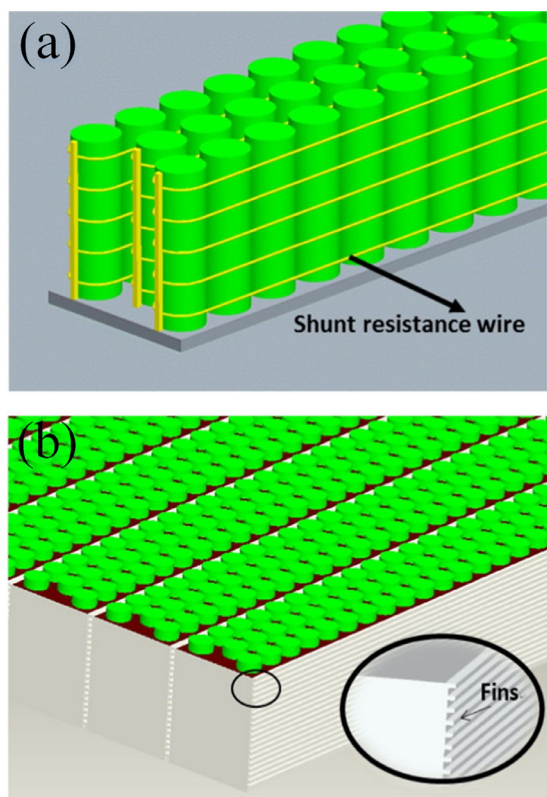


Fig. 16. PCM-based preheating system for batteries. Reproduced with permission from [127] (Copyright 2017 Elsevier): (a) a battery module with resistance wire twined around battery cells, and (b) a battery pack consists of battery modules with CPCM perfused in each module.

to heat the battery and would also absorb a certain amount of heat from the built-in heat source for the use of later short cold stop. Rao et al. [126] compared the heating effect of PCM and air on a prismatic cell from -30°C to 10°C . When the temperatures of the warm air and the PCM are the same (50°C), the cold start-up time of air heating is 6.4 times of PCM heating. Zhong et al. [127] designed a preheating system for battery pack based on paraffin/graphite composite phase change material (CPCM) and insulated resistance wires, as shown in Fig. 16. Battery cells in each module were first wrapped with parallel resistance wires, and the remaining space inside each module was filled with CPCM, which can prevent the temperature of resistance wire from being too high. Experimental results validated that a battery module (consisting of 15 cells, 3 cells in series and 5 cells in parallel) can be heated from -25°C to 10°C in 473 s, with 4 strips of parallel resistance wires, and in 273 s with 5 strips of wires, consuming 4151 J and 2948 J energy, respectively. He et al. [128] placed two heat sheets at the top and bottom of a CPCM-filled battery module, respectively, to preheat batteries from -15°C . The heat sheets were powered by the external power source, and their temperature could be controlled. Their experiments proved that setting the temperature of heat sheets to 50°C is the most energy-saving heating strategy.

The thermal conductivity of PCM plays a fundamental role in their thermal performance for both battery heating and cooling cases. Firstly, it affects the temperature distribution within a battery pack and thus the battery performance. Ling et al. [129] observed a temperature difference of 14.9°C within a battery pack (consists of 20 2.6 Ah 18650 cylindrical cells) using a low thermal-conductivity PCM when batteries were experiencing charge/discharge cycles at -10°C and the non-uniform tempera-

ture distribution cause a voltage difference up to 0.1 V between battery cells. Moreover, PCM with high thermal conductivity allows the heat to be transferred to the battery more quickly during preheating, which is able to reduce the warm-up time. However, the thermal conductivity of conventional PCM is usually limited. In recent years, adding thermally conductive materials to PCM can remarkably improve their overall thermal performance. These CPCMs are found to have better performance in BTMS compared to traditional PCM [130–137]. Although the current literature mainly focuses on the improved cooling effect on batteries by using these CPCMs, the heating effect at low temperatures can also be enhanced when applying this PCM to battery preheating. In addition to CPCM, there is also a research trend of adding nanomaterials to PCM, to significantly enhance their thermal conductivities. Graphene [138], CNT [139], and metal nanoparticles [140] are commonly used as additives in the PCM to significantly improve thermal conductivities of the PCM.

To summarize, the PCM-based thermal management system can only benefit batteries in a short cold stop by delaying their temperature drop. For a long cold stop, built-in heat sources are needed to provide heat for the battery temperature rise. The required thermal properties of PCMs in these two situations are different or even contradictory. Greater latent heat and lower thermal conductivity contribute to slower temperature decrease in a short stop but may be detrimental in a long cold stop since they would lead to slower warming up rate and severer temperature mal-distribution. As such, a tradeoff needs to be made when designing PCM-based BTMS used for both short-term and long-term parking cases. Besides, since adding PCM would inevitably bring additional weight to BTMS, PCMs with less mass are pursued as long as their thermal properties meet the design requirement. In addition, the safety and reliability of the coupled heating system combining PCM and heating elements could be higher than the system with pure heating elements since the addition of PCM can prevent overheating in the battery pack.

4.3. Summary of external heating strategies

The external heating strategies are summarized in Table 1, with some selected cases as the representation of each heating strategy. The preheating systems are contrasted in detail by applying the performance metrics of heating.

Typically, external heating methods need specially designed BTMS to transfer the heat from external heat sources to battery cells during the preheating process, where factors such as the heat transfer patterns and routes, the geometry and layout of the battery cells, the properties of heat transfer media could affect the heating performance. Conventional BTMS, such as air and liquid systems, are economical for commercial applications with high safety and reliability. However, the low heat transfer rate and low heating efficiency are the main challenges in external heating, leading to a prolonged warm-up duration and increased energy consumption, especially when heating large-format Li-ion cells. Moreover, temperature difference within the battery cell and module/pack, affected by the cell geometry, the placement of heating elements, and the thermal conductivity of heat transfer medium, is another critical issue in conventional BTMS.

Efforts can be made in the future to solve the aforementioned problems by enhancing heating efficiency in external preheating systems. Specifically, in convective heating, increasing the heat transfer rate in BTMS is of great significance, which involves changing the flow manner of heat transfer medium to achieve a higher heat transfer rate, applying novel heat transfer fluid with higher thermal conductivity (e.g. nanofluids), as well as optimizing the geometry of flow channels of the heat transfer medium. For conductive heating, better performance can be achieved through sev-

Table 1
Summary of external heating strategies.

Preheating strategies	Reference	Cell capacity	Cell geometry	Ambient temperature	Power source of heating	Applied heating power	Cell mass	Cell temperature increase	Heating time	Energy consumption (for heating a single cell)
Convective heating	[28] [65]	2.2 Ah	Cylindrical	−20 °C	Battery	23.6 W	44 g	40 °C	85 s	6.40%
		37 Ah	Prismatic	−30 °C	External source	–	864 g	30 °C	2100 s	–
Conductive heating	[90] [108]	35 Ah	Prismatic	−40 °C	External source	35 W	1080 g	40 °C	1500 s	17,500 J
		38 Ah	Prismatic	17 °C	Battery	–	–	20 °C (front box);	1200 s	2.5%
		18 Ah	Prismatic	−30 °C	External source	30 W	–	12 °C (rear box) 30 °C	1100 s	2062.5 J
PCM heating	[127]	1.5 Ah	Cylindrical	−25 °C	External source	162 W	45 g	35 °C	273 s	2948 J

% represents the electrical energy consumption in terms of the percentage of battery capacity.

eral methods: (a) optimizing the arrangement of battery cells to increase the effective contact area; (b) applying novel heating elements with higher heating performance (e.g., film-based panel heaters) or coefficient of performance; (c) increasing the thermal conductivity of the heat conduction medium such as the applications of nano-enhanced PCM. Besides these, better thermal insulation can also help to reduce the heat loss to the ambient environment during the heat transfer process, which can also reduce energy expenses during warm-up.

5. Internal heating

Internal heating typically takes advantage of high battery impedance at low temperatures to generate a large amount of electrochemical heat inside the cells when applying a current. The heat generated through the electrochemical process can directly warm up the electrodes and electrolyte of the battery, without passing through the battery surface from the ambient environment to the cell interior. This strategy can heat the battery cell quickly and homogeneously from its interior with reduced heat loss to the ambient environment. In recent years, a variety of internal heating protocols have been investigated, and this section systematically explains these internal heating techniques.

5.1. Internal self-heating

In internal self-heating strategies, batteries generate heat only through their internal resistances (i.e., ohmic resistance and polarization resistance). Since charging batteries at low temperatures is likely to incur lithium plating, batteries have to consume a proportion of their stored energy to heat themselves internally through discharging [28]. For easy implementation, constant current discharge (CCD) and constant voltage discharge (CVD) are the two common operation protocols. According to a simulation study using ECT coupled model, an 18650 cell of 2.2 Ah can be heated from −20 °C to 15 °C within approximately 420 s using CCD (2C discharge) while it can be heated from −20 °C to 20 °C within approximately 360 s using CVD (2.8 V discharge) [28]. Higher heat generation rate can be achieved by either improving the discharge current in CCD or lowering the discharge voltage in CVD to remarkably reduce the battery warm-up time. Nevertheless, high current in CCD and low voltage in CVD should be avoided in case the battery voltage drops below the lower cutoff voltage, which leads to over-discharge. Further relationships between the discharge rate, heating time, and power consumption when using CCD were investigated by Wu et al. [141]. Their study found that both the heating time and battery energy consumption decrease exponentially as the discharge rate increases. Their experimental results revealed that, when using CCD, a commercial 18650 Li-ion battery of 2.6 Ah could be heated from −10 °C to 5 °C in 280 s and 1080 s under 2C and 1C discharge rates, respectively. The energy consumption of 2C-discharge and 1C-discharge situations accounted for 15% and 30% of the battery rated capacity, respectively. Beside CCD and CVD, the discharge current curve can be optimized according to different heating objectives. Du et al. [142] applied a DP approach to optimize the discharge current in order to find a tradeoff between the heating time and capacity fade. Compared with CCD, to heat the battery from −10 °C to 5 °C, this optimized preheating method using dynamic discharge current could reduce the capacity fade, heating time, and power consumption by 5.56%, 1.82%, and 3.04%, respectively. However, the value of the dynamic discharge current is hard to quantify for real implementation because of the computational burden of the DP algorithm.

Internal self-heating can be combined with other external heating techniques to make full use of the output power of batteries during heating [143,144], sometimes in an energy-optimal fashion

[145]. Mohan et al. [145] numerically investigated the optimal discharge current profile in a combined heating strategy to minimize the battery energy consumption, where the battery was heated by both internal heating from the inside and convective air heating from the outside. The optimal current policy was found to be similar to a sequence of constant voltage (CV), constant current (CC) and rest phases. The cell could be heated from -20°C to 20°C within 150 s by using the optimal discharge current. However, the current value is usually uncontrollable in such a battery-powered heating case, making it difficult to be implemented on-board.

To sum up, the internal self-heating strategy typically does not need heating components like external heating and, thus, it has comparably low cost, low complexity and weight addition, high reliability. Low heating efficiency (less than 0.4 for CVD [28]) is the main limitation of the internal self-heating protocol since the battery output power has not been fully utilized to generate heat outside the battery cell, leading to unwanted additional energy consumption during warm-up process. Also, high C-rate operations need to be used carefully to prevent cells from over-discharge as well as avoid accelerated capacity fade, in that the discharge rate has an exponential influence on Li-ion battery aging rate [146,147]. Furthermore, more than 15% battery capacity consumption during warm-up makes this strategy only applicable when battery initial SOC is relatively high. Otherwise, the heating operation is likely to drain the battery energy.

5.2. Mutual pulse heating

Mutual pulse heating takes advantage of the battery and another energy reservoir (e.g. batteries or capacitors) to form an electric circuit and realize the charge/discharge process mutually. The bi-directional current pulses during this process can generate heat inside two energy reservoirs and warm up both of them from sub-zero temperatures. In [28], the cells in a battery pack are classified into two equal-capacity groups, with one group being charged and the other group being discharged. When a DC-DC converter is added between both groups, the discharge voltage of the cells can be enhanced so that the output power of the discharge group can be utilized as the input power for the charge group. During charging, a certain portion of the output power is capable of generating heat inside the battery due to the existence of internal resistance, while the remaining power is stored in charged cells and will be used for discharging later. The charge/discharge roles of the two battery groups change periodically by using pulse signals so that both groups can be heated by each other and warmed up mutually. Simulation results of two battery cells showed that the cell could be heated from -20°C to 20°C within less than 220 s when setting the discharge voltage level to 2.8 V and the pulse intervals to 1 s. This warm-up process only consumed 5% of the battery capacity.

The current profiles in the charge/discharge process can also be optimized to maximize heating efficiency. Mohan et al. [148–150] optimized the bi-directional current profiles by using the warm-up time and energy consumption as objectives. Instead of using a target temperature as an indicator of terminating a pre-heating process, they estimated the battery pulse power capability to determine when the heating should be ended. Results showed that the total energy consumption using CVD is 35% more than this pulse current heating method.

For real EV preheating applications, a Li-ion battery heating system was developed by using an inverter and a motor between the battery and a smoothing capacitor [151]. By adding a relay in the system, the insulated-gate bipolar transistors (IGBT) can be controlled to achieve the charging/discharging processes repeatedly to warm up the battery from low-temperature extreme. This method

can heat the battery from -20°C to 0°C in 5 min and extend the driving range of a PHEV by 13 km.

To sum up, mutual pulse heating makes full use of the charge/discharge processes between the battery and another energy storage device to warm up the battery cells. The output power of the battery and the energy storage device in the heating system has not been wasted compared to internal self-heating so that the energy consumption could be less than 10% of battery capacity, and the warm-up time is usually within 5 min. Moreover, this heating process is highly efficient, with heating efficiency higher than 0.7 even when the DC-DC converter efficiency is only 80% [28]. Nevertheless, some limitations of this heating technique also exist [28]. Mutual pulse heating at high initial SOC levels and using longer pulse intervals are likely to increase the risk of lithium plating, which gives rise to the preference of heating with high-frequency pulses. In addition, the mutual pulse operation needs a complicated circuit and control system, which would increase the number of components as well as the system cost and complexity, particularly in a large-scale integrated battery system.

5.3. Self-Heating lithium-ion battery

In 2016, Wang et al. [34,152] first proposed a novel battery structure by embedding a thin nickel foil with certain electrical resistance as the internal heating element inside the battery to warm up the cell at low temperatures. The structure of this all-climate battery (ACB), also called SHLB, is shown in Fig. 17(a). The nickel foil has two tabs, one of which is welded together with the tabs at the anode, being electrically connected to the negative terminal, while the other extends out from the battery to form a third terminal, the activation terminal (ACT). The working principle of this ACB is illustrated in Fig. 17(b) using electric circuit representation. A switch connecting the ACT with the positive terminal can be controlled according to the cell surface temperature. The switch is left closed only when the battery temperature is low, forcing the current flow through the nickel foil so that large amounts of ohmic heat can be generated to warm the battery internally. Once the target temperature is reached, the heating process is completed, and the switch remains open to make electrons bypass the nickel foil. In this situation, the nickel foil no longer generates heat, and the battery can be charged or discharged as a conventional Li-ion battery with its performance restored.

The activation process allows the temperature of the cell to rise quickly within seconds, which creates favorable electrochemistry inside the battery for charge/discharge as well as restores the cell energy and power capabilities. Results showed that the 7.5 Ah ACB cell can be heated from -20°C and -30°C to a surface temperature of 0°C in 19.5 s and 29.6 s, consuming 3.8% and 5.5% of cell capacity, respectively [34]. Besides, the available 1C discharge energy of the cell could reach 102 Wh kg^{-1} after activation at -40°C while the cell without nickel foil could only have 0.3 Wh kg^{-1} and the discharge power after activation at -30°C was found to be 5–

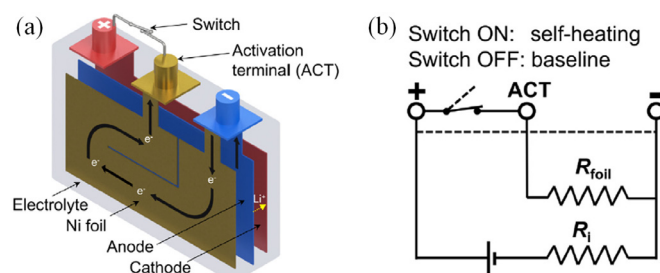


Fig. 17. Internal structure of an ACB. Reproduced with permission from [153] (Copyright 2016 Elsevier).

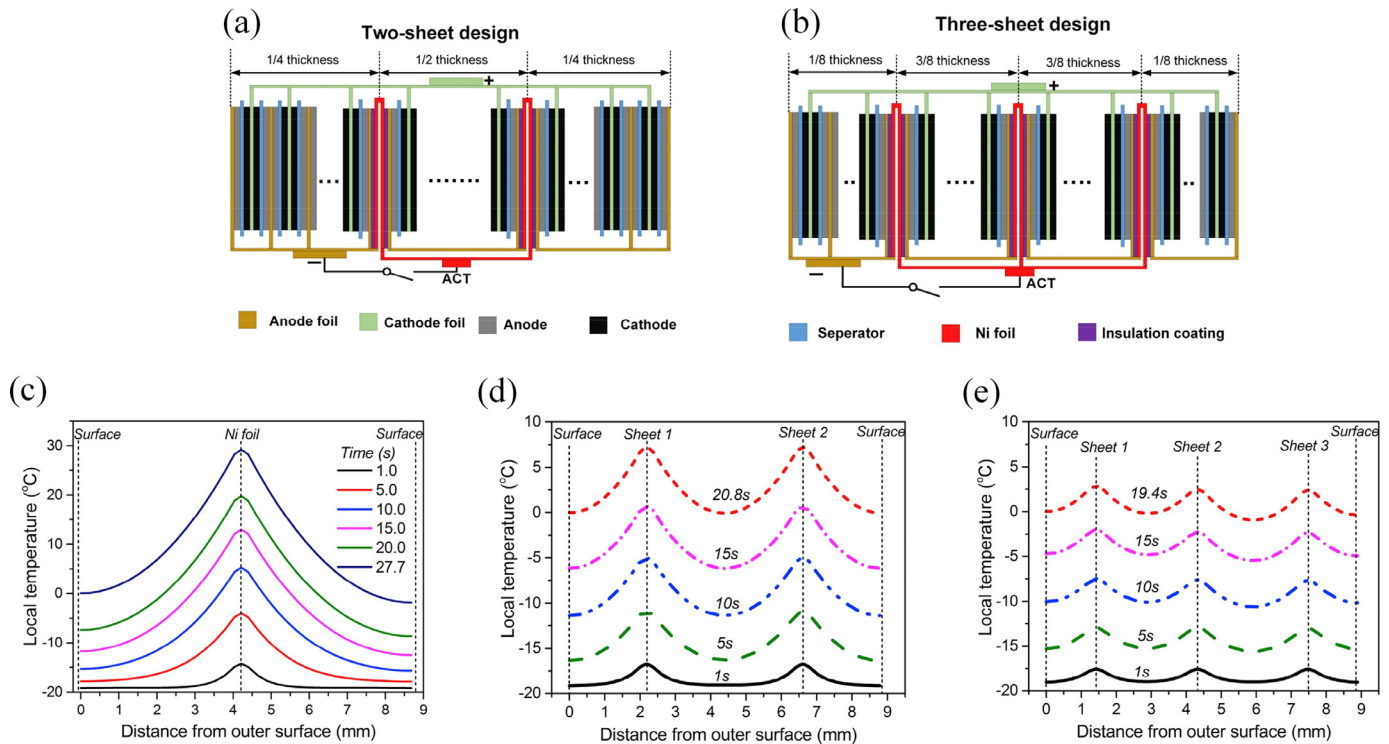


Fig. 18. Internal structure of a multi-sheet SHLB. Reproduced with permission from [155] (Copyright 2016 Elsevier): (a) two-sheet design and (b) three-sheet design; temperature distributions across the cell thickness of (c) single-sheet SHLB, (d) two-sheet SHLB, and (e) three-sheet SHLB.

6 times than the conventional cell at the same temperature [34]. Apart from discharging, pulses of charge and discharge currents can also be utilized during the activation process for lower energy consumption when the external power source is accessible. The ACB cell can be heated from -10°C , -20°C , and -30°C to 10°C in 54 s, 77 s, and 90 s using pulse activation, respectively, consuming less than 2% battery capacity [152]. The current waveforms and duration can be further optimized for less activation time and energy consumption. Furthermore, Zhang et al. [154] proposed an active control strategy for activation called “battery heating while driving” during driving cycles, without waiting for battery warm-up in advance. The control strategy involved heating the battery internally during regenerative braking and rest periods when battery temperature was lower than the pre-set temperature. In the case of braking, the switch was left closed so that the external current from regenerative braking can flow through the nickel foil for heating. During rest periods, the switch still remained closed and the SHLB can discharge through the nickel foil as a reinforced supplement for previous heating. Results showed that the cell could be heated from 0°C , -10°C , -20°C , -30°C and -40°C to 10°C in 13 s, 33 s, 46 s, 56 s and 112 s, respectively.

In SHLB, the majority of heat generation inside the battery comes from the ohmic heat produced by the nickel foil, accounting for 78% on average during the activation process [155]. After such intense heat generation, the temperature uniformity of the cell, which could affect cell performance, is much concerned. Along the in-plane direction, time-sequential images obtained from infrared thermography shows a uniform temperature distribution over the active electrode area during activation but also a hot spot on the ACT as well as a large temperature gradient at the edge [156]. Along the through-plane direction, a large temperature gradient exists from the nickel foil to the outer surface due to insufficient heat transfer. Experimental results showed that when the surface temperature of the cell rose to 0°C after activation, the temperature of the internal nickel foil could reach up to 30°C [155]. Such a

large through-plane temperature gradient was pointed out to trigger non-uniform current distribution and even affect heating time and energy consumption [155].

In order to reduce the temperature gradient inside the SHLB, considerable efforts have been made either in cell structure and cell operation. Yang et al. [155] optimized the SHLB structure by adding more nickel sheets to the battery in the through-plane direction, instead of a single foil in the center. The structure of a multi-sheet SHLB is shown in Fig. 18(a) and (b). Results revealed that the local temperature gradient inside the SHLB during the activation process could be greatly reduced by adding more nickel foils, as shown in Fig. 18(c) – (e). The maximum temperature difference inside a three-sheet SHLB could be controlled within 5°C . In addition, due to cell structure improvement, higher heating efficiency could be achieved, with the activation time reduced by up to 30% and the energy consumption reduced by up to 27%. A detailed comparison of the single-sheet, two-sheet, and three-sheet SHLB in terms of the heating time and the energy consumption is listed in Table 2 for a straightforward reference. Other methods, such as changing the heating protocol of the SHLB, were also reported to reduce the temperature gradient inside SHLB. Lei et al. [157] proposed an intermittent heating method for SHLB at low temperatures. Instead of continuous heating, the Li-ion battery was

Table 2

Comparison of the single-sheet, two-sheet, and three-sheet SHLB schemes in [155].

Structure of SHLB	Activation time (Initial temperature: -20°C ; Target temperature: 0°C)	Battery capacity consumption
Single-sheet SHLB	27.7s	4.15%
Two-sheet SHLB	20.8s	3.23%
Three-sheet SHLB	19.4s	3.03%

heated by cycles of heating and rest. A three-dimensional finite element model indicated that during 30-second heating at -20°C , heating for 0.1 s and then rest for 0.3 s can effectively decrease the temperature difference to 2–3 $^{\circ}\text{C}$, compared to the temperature difference of 10–11 $^{\circ}\text{C}$ in continuous heating case.

Although temperature difference exists inside SHLB during the activation process, the SHLB heating method still exhibits better temperature uniformity than traditional external heating. Lei et al. [158] compared the two-sheet SHLB heating and wide-line metal film heating by using transient three-dimensional heating finite element models. Their results showed that the maximum through-plane temperature difference using wide-line metal films could be three times higher than that using SHLB heating. Besides, they also pointed out that decreasing the heating power and cell thickness can improve temperature uniformity. For large-size Li-ion batteries, the advantage of SHLB heating becomes remarkable. Yang et al. [159] compared conventional external heating strategies, using cell resistance and external electric heater, with the multi-sheet SHLB heating of 40 Ah Li-ion batteries with 34 mm thickness. Results showed that the multi-sheet SHLB heating could achieve more uniform temperature distribution and much less heating time with comparable battery energy consumption in external heating. Moreover, their study also revealed that increasing the heating power in conventional external heating would increase the through-plane temperature gradient and result in local overheating, especially in thick battery cells.

The rapid heating capability of SHLB enables the fast charging with high charge rate after the activation process without lithium plating, which substantially reduces the total time for battery warm-up and charging [152,160]. Yang et al. [160] leveraged the SHLB structure to propose a control strategy that can pre-heat and charge the cell rapidly. According to the proposed strategy, the cell was warmed up from an extreme low temperature to a lithium plating-free (LPF) temperature, by applying an external power source with constant voltage (slightly lower than cell open-circuit voltage) between the positive and negative terminals of SHLB with the switch keeping closed. Then fast charging could be fulfilled once the temperature of the cell reached the LPF value. They demonstrated that a 9.5 Ah SHLB structure cell can be charged to 80% state of charge (SOC) within 15 min even at -50°C , through this process. Therefore, the rapid heating and charging capability of SHLB exhibits great potential in counteracting the problems due to low temperatures, facilitating the application of EV in cold geographical regions.

The cycle life of SHLB has been improved since the internal preheating procedure prior to operation can reduce lithium plating in the later charging process. At low temperatures, the degradation of SHLB mainly comes from normal electrochemical cycling, while conventional cells usually suffer from lithium plating so that their capacity decreases drastically during cycling [152]. A well-controlled preheating-charging process can make SHLB withstand 4500 cycles with high-rate (3.5 C) charging current with reported capacity fade less than 20% at 0°C [160].

To summarize, the rapid heating ability, small energy consumption, extended cycle life, and high charge acceptance make SHLB a paradigm in low-temperature applications of automotive Li-ion batteries. However, disadvantages also exist due to cell structural change. Invasive battery cell structural changes are required, as well as additional controls and switches between battery terminals needed during the operation. This inevitably increases the cost of battery and control complexity, especially for the large-scale integration of SHLBs in EV. Besides, for safety concerns, meticulous operation and precise temperature monitor are essential for the activation process of SHLB to prevent the cell from being over-heated due to the large heat generation rate inside the cell. These two unfavorable factors can reduce the safety and reliability of the BTMS.

5.4. Alternating current heating

AC heating typically applies an AC as the input signal at the battery terminals to generate heat inside the cell. The fast and periodical charging/discharging processes enable the battery to keep its SOC relatively stable. Different from the aforementioned three internal preheating categories, this sort of strategy can be usually achieved without extra battery energy consumption during warm-up by using an external power source. Moreover, AC heating was demonstrated to be one of the most efficient preheating approaches, which can heat the battery quickly and uniformly, compared with external warm-up strategies [57,58]. Among various AC signals, sinusoidal alternating current (SAC) is the most commonly used AC heating, and its current amplitude and frequency can be adjusted for greater heat generation inside the cell.

Hande et al. [161–164] first investigated the feasibility of using 10–20 kHz AC to heat automotive nickel-metal hydride (NiMH) at low temperatures and found that the cells could be heated from subzero temperature to room temperature within 8 min. Ji et al. [28] proposed an AC heating strategy based on the electrochemistry of Li-ion batteries. An ECT coupled model was applied to investigate the characteristics of the warm-up effect by applying AC. Their results showed that using a voltage signal $V(t) = 3.8 - \cos(2\pi ft)$, the cell can be heated from -20°C to 20°C in 340 s, when the frequency of voltage signal is 0.01 Hz and the cell surface is assumed to be adiabatic. The warm-up duration can be further reduced by increasing the signal frequency, and the associated heating times are 170 s and 80 s with frequencies of 60 Hz and 1000 Hz, respectively. Besides, two frequency regions, namely 0.01–0.1 Hz and 1–1000 Hz, were recommended to reduce the heating time at low temperatures.

The warm-up time of SAC heating is largely dependent on the current parameters such as amplitude and frequency since these two parameters can affect the heat generation rate inside the battery cell. Specifically, the current amplitude can directly affect the heat generation inside the battery cell, while the battery impedance often varies with current frequency and cell temperature [47]. In the current literature, efforts have been made to study the influence of SAC parameters on the preheating effect. Zhang et al. [47] revealed the relationship between SAC parameters and battery warm-up time based on a heat generation model in the frequency domain. The heat generation rate inside the cell was calculated based on current amplitude, current frequency and the impedance of an equivalent electrical circuit (EEC) battery model, which is shown in Fig. 19(a). The effect of SAC parameters on heating effect under different heat transfer conditions was illustrated with contours of heating time, as shown in Fig. 19(b)–(d). They pointed out that the increase of SAC amplitude, the decrease of current frequency, and the improvement of thermal insulation conditions could shorten the preheating time. Furthermore, they also concluded from these contours that the current amplitude has a greater impact on the preheating time than the frequency in low-amplitude and low-frequency range, whereas, in the high range of both parameters, the frequency is more decisive [47].

To shorten battery warm-up time and maximize heat generation inside the battery, the current amplitude and frequency of the applied SAC need to be adjusted to suitable values according to cell temperature. Ruan et al. pointed out that applying SAC with a constant frequency to warm up the battery is much more feasible than using varied frequencies for engineering applications [165]. They investigated the optimal SAC frequency for the maximum heat generation rate during the overall preheating process at different temperatures, based on a reduced electro-thermal coupled (RETC) model [166]. Li et al. [167] concluded from experiments that low-frequency SAC within 100 Hz could heat the battery effectively from low temperatures.

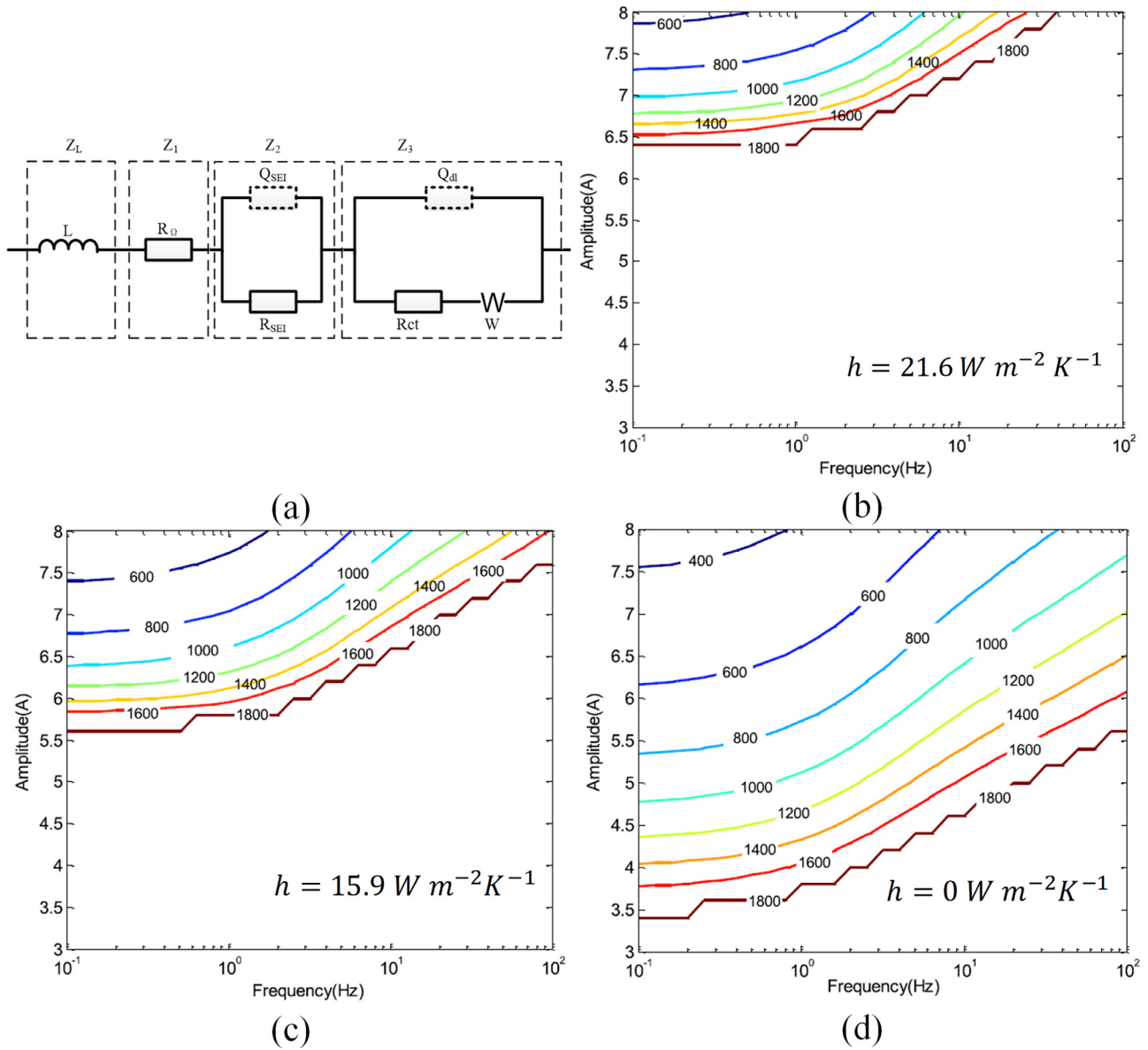


Fig. 19. EEC model used in AC heating and preheating effects with different SAC parameters (time unit: second). Reproduced with permission from [47] (Copyright 2014 Elsevier).

Since regulating the current frequency during the AC heating process is difficult to realize, a mainstream approach to accelerating the temperature rise of Li-ion battery cells is to adjust the current amplitude, once the SAC frequency has been determined. Besides, when the battery temperature is rising, the heat generation rate inside the cell would gradually decline with the decrease of its impedance if the current amplitude remains constant. Therefore, the amplitude of SAC needs to be adjusted during the preheating process. The key issue of this current regulation is to maximize the internal heat generation rate without producing detrimental effects on battery health. Therefore, constraints are usually imposed to restrict the maximum current amplitude to guarantee battery health. Ge et al. [33] adopted lithium plating as the constraint to adjust the current amplitude of SAC and proposed a step-wise preheating method at low temperatures. Through calculating the over-potential at the anode area of a three-electrode Li-ion battery and maintaining it positive, the maximum allowable current amplitude with lithium plating prevention was determined, which was found to increase with the rise of the current frequency as

well as the battery temperature. The amplitude of the SAC in each preheating step could be modified according to the battery temperature. Results showed that the 1 Ah pouch cell in the study could be heated from -20°C to 5°C within 800 s at a 100 Hz frequency. Ruan et al. used the polarization voltage in the RETC model as the constraint to restrict the maximum current amplitude based on a constant SAC frequency [165]. Their results showed that under the current frequency of 1377 Hz (the optimal frequency for the overall preheating process), the battery can be heated from -15.4°C to 5.6°C in 338 s. Guo et al. [46,168] used the battery terminal voltage as the constraint to develop a preheating strategy based on amplitude-variable SAC profiles. The dynamic terminal voltage of the battery, which was described by applying the Butler-Volmer equation, was restricted between the minimum and the maximum voltage limits during the preheating process to prevent the battery from over-discharge and over-charge. The optimal input current amplitude was calculated in a timely manner to maximize the heat generation inside the cell after selecting a suitable frequency. Experimental results showed that a single battery cell could be

heated from -20.3°C to 10.02°C in 13.7 min while the battery pack with four cells in series could be heated from -20.84°C to 10°C in 12.4 min, with SAC frequency of 10 Hz.

Apart from SAC, other AC waveforms such as rectangular wave and step-growth wave were also applied for battery preheating. Zhao et al. [169] excited batteries using current pulses with charge rates 0.75–2 C and discharge rates 3–4 C before CC–CV charging at the subzero environment. The battery could be heated from -10°C to 3°C in 10 pulse cycles. Ruan et al. [170] synthesized a step-growth charge current and a constant discharge current, where the duration of charge and discharge process was set to be 4 ms, to internally warm the battery up. Specifically, the amplitude of the charge current had a stair increase; every time the battery temperature increased by 2°C and the amplitude of the discharge current remained unchanged. This method allowed the battery to achieve an approximately linear temperature rise over time. Results showed that a 35 Ah battery could be heated from -10°C to 2°C within 18 min. Zhu et al. [171] compared the effects of current waveforms (sinusoidal and rectangular current profiles) on the temperature change of a 2.3 Ah 18650 battery. For both current profiles (10 A, 30 Hz, and 600 s heating time), the battery can be heated from -24°C to 7.79°C using the sinusoidal current, and from -24°C to 25.6°C using rectangular current. This result was due to a higher root mean square (RMS) value of the rectangular current profile. Zuniga et al. [172] applied a low-frequency (0.01 Hz) square-wave current to preheat a 100 Ah prismatic cell and compared this strategy with an external heating option, i.e., sandwiching the prismatic cell with two electric heating pads. Given the same heating power of 50 W and heating time of 1800 s, although both heating strategies exhibited a similar cell temperature rise (from -20°C to 14.9 – 15.9°C), square-wave current heating could achieve more quick temperature rise of the battery core than that in external heating.

While most AC heating strategies typically require EV to have access to external power sources such as charging stands, there is a trend to develop onboard AC heating method by designing a specific electrical circuit to generate AC without external power supply, which can effectively reduce the inconvenience of AC heating caused by insufficient external power facilities. Jiang et al. [49] designed a soft-switching resonance circuit to generate AC by using battery power. This resonance circuit can generate both AC and direct current so that the superimposed current is able to internally heat a large-size automotive Li-ion battery pack (12 35Ah laminated batteries connected in series) with lithium plating avoidance, in which the current limitations were developed based on a battery EEC model. The whole battery pack could be heated from -20.8°C to 2.1°C within 600 s with battery energy consumption of 6.64%. The maximum temperature difference in the pack was less than 1.6°C during preheating. Shang et al. designed various electric circuits to realize onboard AC heating [173–175]. A periodic ramped discharged current with a certain amplitude and frequency can be generated through the designed circuits and preheat Li-ion batteries from -20°C to 0°C within several minutes, with less than 5% of battery energy consumption.

Although the AC heating process can warm up the Li-ion battery quickly and uniformly from low temperatures, the effect of AC heating on battery aging is still the main concern, yet the related works are limited. AC parameters, especially the current amplitude and frequency, would affect internal electrochemistry of Li-ion battery and need to be systematically investigated with respect to their effect on the battery aging mechanism. In most works, the current amplitude is the main factor to influence the occurrence of lithium plating during AC heating because it directly affects the anode potential [33,49,165]. The current frequency was found to affect the kinetic and transport process of Li-ion cells [28]. Zhu et al. [171] provided a possible model to explain the ef-

fect of AC heating on battery aging. At high frequencies, the charge transfer and the diffusion process are bypassed due to short excitation duration so that lithium plating does not occur, as shown in Fig. 20(a). With the decrease of current frequency, both processes become active, but the intercalated lithium ions during the charging process would de-intercalate during the subsequent discharging period. Thus there is no dead lithium produced, as shown in Fig. 20(b). At low frequencies, when the current amplitude becomes increases, the produced lithium cannot be fully de-lithiated during the prolonged AC excitation period due to complex and nonlinear electrochemical reactions. With some side reactions, the dead lithium could be created, causing irreversible battery capacity loss, as shown in Fig. 20(c).

To experimentally investigate the effect of AC heating on battery aging, most of the literature focuses on short-term degradation by examining the battery capacity after tens of heating cycles [46,47,165]. The capacity tests of the battery showed a slight variation of charge/discharge capacity after AC heating cycles, suggesting no occurrence of apparent battery degradation in the short term [46,165]. The long-term effect of AC heating on battery degradation has not yet been investigated until recently. Guo et al. [176] investigated the aging effect of 210 repeated AC heating cycles (amplitude-varying AC after optimization at a high frequency of 530 Hz) on a three-electrode Li-ion battery at -20°C by applying capacity calibration and incremental capacity analysis, which show no detrimental effect on cell health. Zhu et al. [32] systematically explored the effect of AC heating on the battery state of health (SOH) at -25°C through 240 AC heating cycles. Tests of the battery capacity, DC resistance, electrochemical impedance spectroscopy (EIS), and observations of battery internal morphology after disassembly indicated that irreversible battery damage did not occur after 240 AC heating cycles even with a low frequency (0.5 Hz), as long as the battery voltage limits (3.7 V/2.5 V) were satisfied. Jiang et al. [49] explored the effect of AC on the lifetime of a large-format Li-ion battery pack by repeating 600 heating cycles at -20°C . Battery consistency variation, capacity loss, and resistance increase were not found to be obvious in such a pack level. So far, AC heating approaches have been validated to be effective and benign to Li-ion batteries at extremely low temperatures, if the current parameters are selected properly.

To sum up, typical AC heating with well-selected current parameters can achieve safe, efficient and reliable heating at low temperatures without consuming battery energy. Besides, the heating circuit is quite simple, which eliminates the addition of extra components and thus has low cost and complexity. Nevertheless, the adoption of AC source during heating requires the EV to have access to external power sources except that the EV has equipped with an onboard AC generation circuit. More importantly, until now, the effect of AC heating on Li-ion battery aging has not been investigated thoroughly from perspectives of the electrochemical mechanism but only been experimentally examined through battery capacity analysis after repeated preheating cycles. Understanding the effect of AC current on battery aging behavior could achieve battery warm-up towards a more efficient and health-conscious way. Furthermore, for module/pack level, the cell resistance inconsistency gives rise to different heat generation rate inside each cell and thus cause a temperature gradient inside the battery module/pack.

5.5. Summary of internal heating strategies

The internal heating strategies are summarized in Table 3, with some selected cases as the representation of each heating strategy. The preheating systems are contrasted in detail by applying the performance metrics of heating.

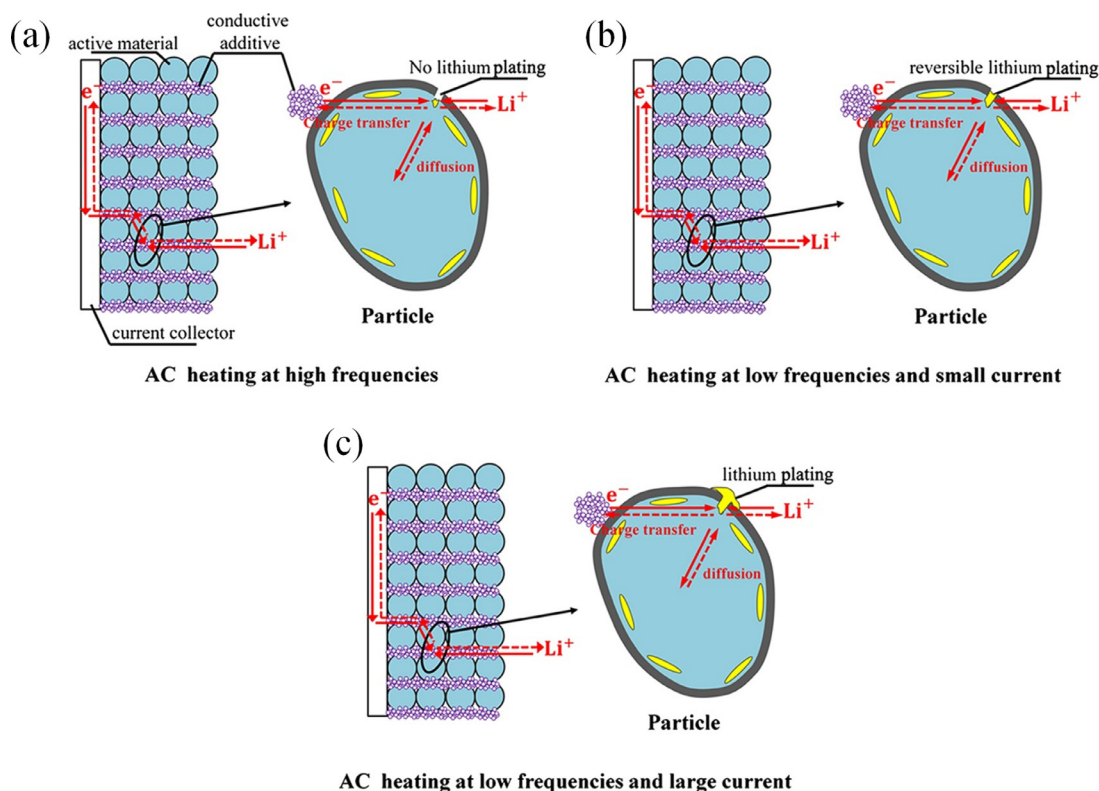


Fig. 20. Effect of AC heating on Li-ion battery aging with different current frequencies. Reproduced with permission from [171] (Copyright 2016 John Wiley & Sons).

Generally, internal heating strategies heat a battery quickly with low system complexity since heat is generated directly inside the battery, and this process does not need a long heat transfer route compared to external heating. The heating time of these approaches varies from tens to hundreds of seconds, which is shorter than that in most external heating strategies. Among the four types of internal heating methods, only the AC heating uses an external power source in most situations, whereas the others need to consume battery energy. One of the main concerns for internal heating strategies lies in concomitant battery degradation. For internal self-heating and SHLB, since the battery discharges during heating, direct damage such as lithium plating does not happen, but high rate operations will aggravate aging in the long term. For the mutual pulse heating, using a low pulse frequency and heating at a high initial SOC should be circumvented since both of them increase the risk of lithium plating. For the AC heating, the current with a low frequency should be used cautiously with additional limitations (such as voltage bounds) to avoid irreversible damage to the battery. Using a high frequency in AC heating is conducive to reducing battery capacity loss.

6. Remarks and future trends

The ultimate goal of battery warm-up is to restore the battery performance as quickly as possible in cold climates, taking into account energy consumption, resultant battery aging, temperature uniformity, overall cost, system complexity, safety, and reliability. It is highly anticipated that the continual improvements of battery preheating strategies will help EV to handle various climate conditions in different regions over the world. As discussed extensively previously, the various battery preheating strategies exhibit

pros and cons. These strategies are qualitatively compared in terms of meeting design requirements (a)–(g), as listed in Table 4.

External heating strategies typically require a customized external thermal management system that considers the cell geometry and arrangement. Their energy consumption, preheating duration, effects on battery aging and temperature uniformity often vary from method to method. Generally, air and liquid management have been primarily adopted in commercial EVs due to their maturity with relatively low cost, high safety, and reliability. Both strategies have excellent compatibility with the off-the-shelf cooling systems, so that slight changes are required to be made to the original system. Heating methods with resistors, heat pipes, and PCM are still in the laboratory stage and need further investigations, even though their heating performance sometimes is better than air and liquid management. Other techniques, such as heat pump heating, Peltier-effect heating, and burner heating, are three possible solutions, but their heating performance still remains to be examined. However, low heating efficiency is the major challenge for external heating, which leads to increased energy consumption and prolonged heating time. Besides, temperature uniformity and weight increase are also inferior, compared to internal heating.

Internal heating techniques typically warm up batteries faster and more uniformly, with other advantages in terms of energy consumption, temperature uniformity, cost, and weight increase. However, all of these heating technologies have not been commercialized due to their immaturity in the battery module/pack level. The internal self-heating can be applied during the driving to maintain the battery temperature, in which the battery output power can be used for the operation of other onboard electronics. Mutual pulse heating can be applied in the presence of an ultra-capacitor to generate current pulses to preheat batteries, but pulse dura-

Table 3
Summary of internal preheating strategies.

Preheating strategies	Reference	Cell capacity	Cell geometry	Ambient temperature	Power source of heating	Heating operation	Cell mass	Cell temperature increase	Heating time	Energy consumption (for heating a single cell)
Internal self-heating Mutual pulse heating	[28]	2.2 Ah	Cylindrical	−20 °C	Battery	2.5 V CVD	44 g	40 °C	196 s	18.00%
	[141]	2.6 Ah	Cylindrical	−10 °C	Battery	2 C CCD	45 g	15 °C	280 s	15.00%
	[28]	2.2 Ah	Cylindrical	−20 °C	Battery	Discharge voltage: 2.2 V; Pulse interval: 1 s	44 g	40 °C	80 s	5.00%
	[148]	2.3 Ah	Cylindrical	−20 °C	Battery	Pulse current with optimized amplitude	70 g	32.3 °C	278 s	10.00%
Self-heating lithium-ion battery Alternating current heating	[155]	10 Ah	Prismatic	−20 °C	Battery	Remains the switch of a three-sheet SHLB closed	–	20 °C	19.4 s	3.03%
	[33]	1 Ah	Pouch	−20 °C	External source	Current frequency: 100 Hz, Amplitude: varied	25.6 g	25 °C	800 s	–
	[46]	3 Ah	Cylindrical	−20.3 °C	External source	Current frequency: 10 Hz, Amplitude: varied	46 g	30.3 °C	822 s	–
	[49]	35 Ah	Prismatic	−20.8 °C	Battery	Alternating current combined with direct current	1010 g	22.9 °C	600 s	6.64%
	[165]	2.9 Ah	Cylindrical	−15.4 °C	External source	Current frequency: 1377 Hz, Amplitude: varied	48 g	21 °C	338 s	–

% represents the electrical energy consumption in terms of the percentage of battery capacity.

Table 4
Qualitative comparison of different heating methods.

Preheating strategies	Energy consumption	Preheating duration	Effect on battery aging	Temperature uniformity	Cost	Weight increase	Safety and reliability
External heating	Air heating	***	***	***	*	*	***
	Liquid heating	****	****	*	****	*	****
	Heat pump heating	**	***	*	***	***	****
	Resistance heating	***	***	**	**	**	**
	Peltier-effect heating	***	****	*	**	***	***
	Heat pipe heating	***	***	*	***	***	****
	Burner heating	****	**	*	****	***	*
	Phase change material heating	****	***	*	***	***	***
Internal heating	Internal self-heating	****	*	**	****	*	****
	Mutual pulse heating	*	*	***	****	**	**
	Self-heating lithium-ion battery	*	*	*	***	****	**
	Alternating current heating	*	**	*	****	*	****

tion and amplitude need to be modulated to avoid lithium-plating. SHLB and AC heating could achieve a satisfactory tradeoff in heating performance. However, for SHLB, different battery manufacturing, packaging, and management techniques are required for large-scale applications, while for AC heating, insights into the heating management of the large modules/packs are still lacking.

Despite the extensive research progress made so far, how to preheat batteries from subzero temperatures efficiently is still a challenge and remains to be unsolved. Thus the future trends are suggested from the following aspects to encourage more breakthroughs in this research area:

- The heat transfer process in the battery preheating system needs to be comprehensively designed from thermal science perspectives to enhance the heating performance, particularly in external heating. The heat transfer path and patterns are required to be optimized in order to reduce the heat transfer distance, enhance the heat transfer coefficient, and minimize the unwanted heat loss to the ambient environment. Therefore, better thermal insulation, adding more thermally conductive materials (e.g., nanofluids and CPCM), and applying more thermally efficient heating elements (e.g., heat pumps and film-based panel heaters) would also be beneficial to such preheating systems.
- The development of model-based control strategies in BTMS can achieve optimal battery heating for both external and internal heating. Current studies primarily focus on the design of preheating systems and the exploration of novel heating approaches. Although some inherent parameters of such heating systems have been investigated in terms of their effects on heating performance, the control optimality, which helps to achieve better heating performance through heating process controls, has seldom been studied [144,145,148,150]. Nevertheless, model-based preheating control strategies typically require applicable models that are suitable for control and implementation. Therefore, the key challenge is to develop control-orientated battery preheating models with adequate accuracy as well as high computational efficiency, during which precise modeling of battery thermal behavior (at the cell, module, and pack level), system heat transfer characteristics, and system heat generation are necessary.
- The preheating strategies need to be further explored in a battery module/pack level since cell temperature homogeneity in a pack is critical to the overall performance of the battery pack and would affect its aging processes. If there is no heat generation inside the battery pack, namely the battery heating is a pure heat transfer problem, the effect of surrounding-to-cell heat interaction characteristic on the temperature uniformity of the pack can be studied. If heat is generated inside the battery pack, different cell heat generation amounts caused by cell resistance inconsistency could contribute to the thermal gradient inside the pack and, thus, need to be considered.
- The effect of preheating on battery aging remains to be investigated systematically, especially for AC heating. The effect of current parameters such as amplitude and frequency on battery aging needs to be studied from a perspective of electrochemical mechanisms inside a Li-ion battery. Electrochemical models governing the kinetic and transport processes at the anode under an AC signal load can be established to reveal the effects of AC parameters on aging in an explicit manner. In this way, the ultimate current limits in AC heating could be fully explored to boost heating performance without harming the battery, making AC heating a favorable paradigm in battery low-temperature applications.

7. Conclusions

This paper presents the state-of-the-art preheating strategies for automotive Li-ion batteries at subzero temperatures. First, the effect of low temperatures on battery performance and material properties are reviewed briefly. Second, the thermal science involved in battery warm-up, the key design factors for battery heating, as well as the classification of warm-up methods, are elucidated. Two categories of heating approaches, namely external heating, and internal heating, are systematically reviewed in terms of their underlying principle, strengths, weaknesses, and potential improvements. Finally, a qualitative comparison of these heating strategies has been made based on the performance metrics and their technique maturity. Additionally, some important future research trends are also provided.

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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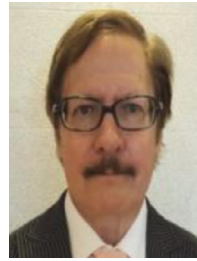
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