

A comprehensive review of lithium-ion batteries used in hybrid and electric vehicles at cold temperatures



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HIGHLIGHTS

- We present a comprehensive review on lithium ion batteries used in hybrid and electric vehicles under cold temperatures.
- The weak performances of lithium-ion batteries in cold weather are explained.
- The influence of low temperatures on the aging mechanisms of lithium ion batteries is discussed.
- The different uses of thermal strategies in an automotive application are proposed.

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ABSTRACT

Because of their numerous advantages, lithium-ion (Li-ion) batteries have recently become a focus of research interest for vehicle applications. Li-ion batteries are suitable for electric vehicles (EVs) and hybrid electric vehicles (HEVs) because of advantages such as their high specific energy, high energy density, and low self-discharge rate in comparison with other secondary batteries. Nevertheless, the commercial availability of Li-ion batteries for vehicle applications has been hindered by issues of safety, cost, charging time, and recycling. One principal limitation of this technology resides in its poor low-temperature performance. Indeed, the effects of low temperature reduce the battery's available energy and increase its internal impedance. In addition, performance-hampering cell degradation also occurs at low temperatures and throughout the entire life of a Li-ion battery. All of these issues pose major difficulties for cold-climate countries. This paper reviews the effects of cold temperatures on the capacity/power fade of Li-ion battery technology. Extensive attention is paid to the aging mechanisms of Li-ion batteries at cold temperatures. This paper also reviews several battery models found in the literature. Finally, thermal strategies are detailed, along with a discussion of the ideal approach to cold-temperature operation.

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1. Introduction

Currently, hybrid electric vehicles (HEVs) and electric vehicles (EVs) promise a future of green travel in which fuel-consuming engines are replaced with electric motors, thus reducing our dependence on fossil energy and ultimately producing less harmful emissions. Such vehicles can be plugged in at home overnight or at the office or in a parking space during the day, using electricity that is generated at a centralized power station or even by renewable sources. The key component to the achievement of these electrical systems is the energy storage system, namely, the battery technology.

The lithium-ion (Li-ion) battery has been the most common choice for telephone communication and portable appliances because of its many advantages, such as high energy-to-weight and power-to-weight ratios (180 Wh/kg and 1500 W/kg, respectively) and low self-discharge rate [1,2]. In addition, among all rechargeable electrochemical systems, Li-ion technology is the first-choice candidate as a power source for HEVs/EVs. However, this technology is still delicate and affected by numerous hindrances, such as issues of safety [3], cost [4], recycling [5], and charging infrastructure [6].

Currently, another issue preventing the wide-spread adoption of EVs and HEVs in cold-climate countries (Canada, Russia, and the Scandinavian Peninsula) is their low-temperature operation. Despite the additional energy consumed for cabin heating, the limiting factor is most closely related to the significantly reduced energy and power capabilities of Li-ion cells. Fundamentally, decreasing the temperature of such a cell causes a slowdown of the chemical reactions, affecting the charge-transfer kinetics [7] and leading to low electrolyte conductivity [8] and a decreased diffusivity of lithium ions within the negative-potential electrode (anode) [9]. These limitations reduce the available energy and power of the cell and also cause global performance failure in Li-ion batteries at low temperatures [10].

In addition to poor performance, the anode undergoes a more prevalent and hazardous mechanism at low temperatures: lithium plating [11]. The net effect of the cold is high polarization of the graphite anode, which brings the anode potential close to the potential of lithium metal [12]. In this case, slow lithium-ion diffusion into graphite (anode potential) leads to the plating of metallic lithium during charging [13]. Under these circumstances, lithium plating occurs on the electrode surface, thereby reducing the energy and power capabilities of the Li-ion battery and causing severe battery degradation.

Recently, thermal strategies for cold battery operation have breached the market of hybrid and electric vehicles as a result of the difficulties induced by the effects of cold discussed above. Interest in these strategies has considerably intensified and generated many studies concerning the cold-weather operation of electrochemical systems. For instance, some such studies [14–16] have considered warming the cell before operation using a heating system powered by either an external source or simply the battery itself.

To simulate and validate these new battery thermal management systems and to enhance the energy performances of battery packs, various electro-thermal models and aging models have been developed.

This paper reviews the effect of cold temperatures on the performance of Li-ion batteries. The low-temperature aging mechanism is briefly considered. Furthermore, insights into thermal modeling investigations are provided; these include descriptions of the aging models. Finally, based on an analysis of the literature, the state of the art of Li-ion thermal management systems for optimal performance in winter applications is summarized.

The remainder of this paper is organized as follows: Section 2 presents the effects of cold on Li-ion batteries. Section 3 describes the thermal and aging models. Section 4 discusses the state of the art in battery thermal management. Finally, conclusions are given in Section 5.

2. Effect of cold effect in Li-ion batteries

The performance and life of Li-ion batteries are both affected by their temperatures of operation. Generally, they suffer significant losses in subzero-temperature environments because of reduced energy and power capabilities as well as severe battery degradation due to lithium plating. The purpose of this paper is to document the effects of cold weather on Li-ion cells from two perspectives: performance loss and aging.

2.1. Low temperature performance

Because Li-ion battery performance is strongly associated with temperature, it is crucial to comprehend why this technology suffers severe setbacks at low temperatures. The performance of Li-ion batteries is clearly reduced at lower temperatures. For example, it has been reported that for the same current, the available energy of a Li-ion cell at $-20\text{ }^{\circ}\text{C}$ is 60% of the room-temperature

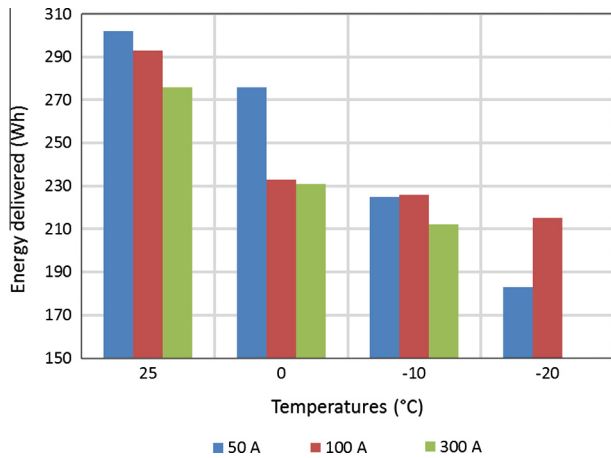


Fig. 1. Outputs characteristics of LiFeMnPO₄ cells in different-temperature tests [18].

value [17]. Fig. 1 shows the test results and Wh characteristics of an actual HEV battery at four different ambient temperatures (25 °C, 0 °C, -10 °C and -20 °C) and three discharging currents [18]. The battery tested was a prismatic 100-Ah LiFeMnPO₄ cell with a working voltage between 2.5 V and 3.8 V.

The low-temperature performance of Li-ion cells can be attributed to several factors, including the motion of lithium ions in the electrolyte solution (electrolyte conductivity), cell design, electrode thickness, separator porosity and separator wetting properties. First, it has been reported that the poor performance of Li-ion batteries at low temperatures is due to the electrolyte, as shown in Fig. 2. The solution conductivity increases with temperature; thus, the mobility of the ions decreases in cold environments, causing a significant rise in internal resistance.

Therefore, previous analyses have predominantly focused on the development of low-temperature Li-ion electrolytes with low freezing points and high ionic conductivities [9,19–23]. In [8,24], the authors investigated a number of low-temperature Li-ion

electrolytes in experimental Li-ion cells, involving MCMB anodes and LiNiCoO₂ cathodes. In this study, the results of discharge characterization tests performed on cells over a large temperature range (+30 to -70 °C) and at different rates (C/100 to 3C) demonstrated that all carbonate-based electrolytes exhibit adequate conductivity for good performance at low temperatures. Indeed, this approach led to improved low-temperature performance.

However, it has been suggested that the contribution to the poor performance of Li-ion batteries at low temperatures due to the ionic conductivity of the electrolyte is not as significant as expected. In many cases [10,25,26], the poor low-temperature performance of Li-ion batteries is linked to a high charge-transfer resistance. The authors of [10] stated that for a cell with a LiBF₄-based electrolyte, the resistance of the charge-transfer process in the Li-ion cell substantially increases as the temperature drops below -20 °C. Their results obtained using a novel approach based on LiBF₄ salt instead of LiPF₆ suggest that an electrolyte made of LiBF₄ salt has a lower charge-transfer resistance and, therefore, an improved low-temperature performance. In addition, an analysis of the impedance spectra of symmetric cells in [26] demonstrated that the poor low-temperature performance of Li-ion batteries is related to the high charge-transfer resistance of the graphite and cathode. Moreover, the charge-transfer resistance is greatly affected by the state of charge (SOC) of the electrodes, such that at low temperatures, charging a discharged Li-ion battery is more problematic than discharging a charged battery. Nevertheless, the latest preliminary studies by Huang et al. [27] suggest that the main factor limiting the low-temperature operation of Li-ion cells is related to the graphite anode instead of the cathode. Indeed, the primary cause of poor Li-ion cell performance at low temperatures lies in the Li⁺ diffusion in the carbon anode, not in the electrolyte. In another study [9], the authors attempted to verify Huang's conclusion by directly quantifying the chemical diffusion coefficient of a Li-ion cell in a low temperature range; their results are depicted in Fig. 3. They observed, first, a spectacular decrease in lithium-ion diffusivity at low temperatures of 0 °C and below, and second, according to Fig. 3, lithium ions have a lower diffusivity in delithiated graphite (the discharged state) than in lithiated

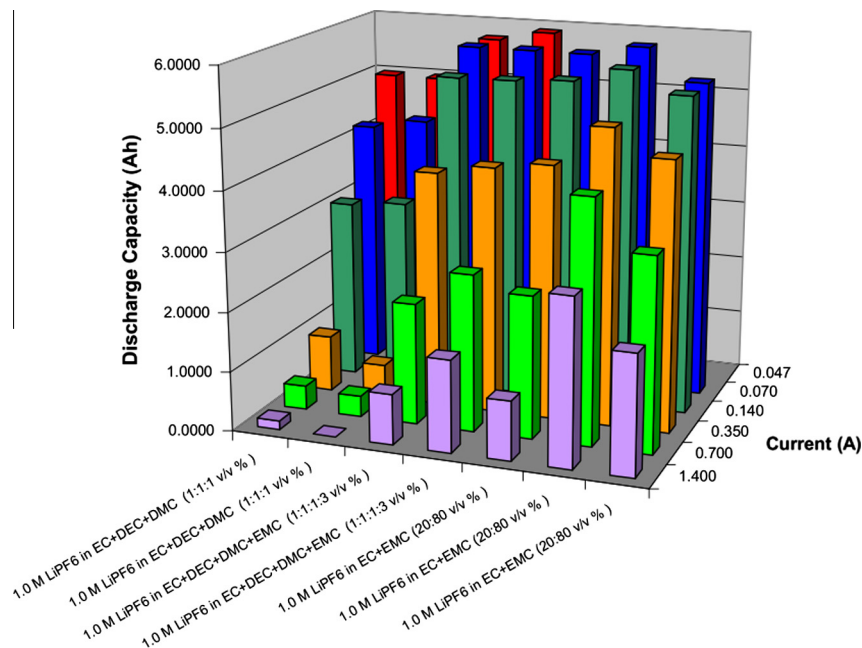


Fig. 2. Performance of 7Ah cells at -60 °C with different low temperature electrolytes [17].

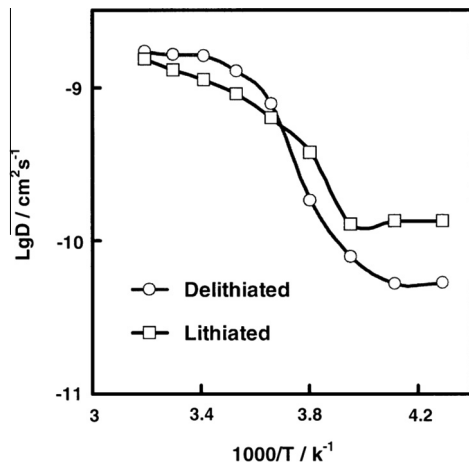


Fig. 3. Diffusivity, $Lg D$, of lithium ions in graphite as a function of $1/T$ for lithiated (squares) and delithiated (circles) graphite [9].

graphite (the charged state) in a cold environment. Their result accentuates the fact that charging a cold discharged cell is more difficult than a discharging a charged cold one, which concurs with the findings stated above about the rise of the charge-transfer resistance.

Finally, the net effect of the phenomena discussed above is strong polarization of both electrodes, which directly affects the cell's electrical performance (voltage drop). The literature [1] ascribes this drop to the Nernst equation (Eq. (1)):

$$OCV = E_0 + \frac{RT}{nF} \ln \frac{a(ox)}{a(red)} \quad (1)$$

where a_i is the activity of the relevant species (ox for oxidizers and red for reducers), R is the gas constant (J/mole/K), T is the temperature (K), OCV is the open-circuit voltage (V), and E_0 is the standard electrode potential (V). In a cell, the OCV of a cell is given by the Nernst equation, which relates the OCV to the standard electrode potential (E_0), temperature, and activity. The OCV is also known as the equilibrium voltage of a cell when no current is applied. Temperature will influence the OCV , for example, at low temperatures, OCV is decreasing and the total voltage undergoes a voltage drop. As

a result, the performance of a Li-ion cell suffers a decrease in energy and power at low temperatures because of the high resistance and low diffusion of Li^+ ions at the anode/electrolyte interface. Additionally, because of significant aging mechanisms at low temperatures, capacity can be irreversibly lost due to operation at low temperatures.

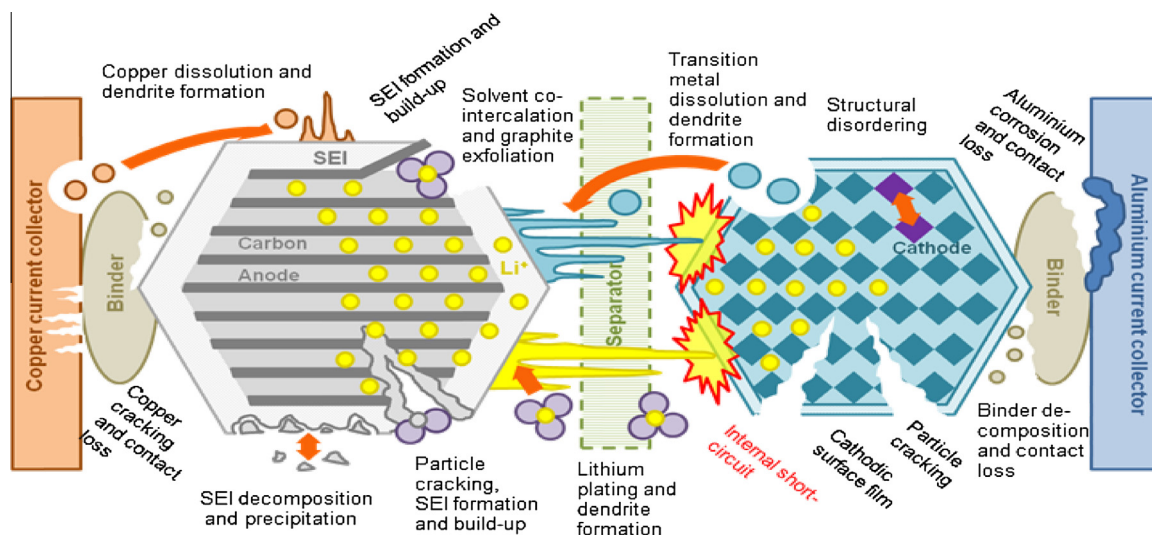
2.2. Aging of Li-ion batteries

2.2.1. Aging effect

Aging first occurs at the interfaces between the electrolyte and the electrodes because of the chemical composition of the cell electrolyte [28]. Aging mechanisms can be either mechanical or chemical and are strongly dependent on electrode composition. As a rule, two principal effects of battery aging can be identified: impedance rise and capacity fade [29]. Performance loss results from various chemical-based mechanisms, which depend on the electrode materials. The consequences of these mechanisms for Li-ion cells are as follows:

- A passivation layer forms around the anode, known as the solid electrolyte interphase (SEI), and its growth leads to an impedance rise at the anode [30]. Typically, SEI formation occurs principally at the beginning of aging, but its growth proceeds throughout operation and storage.
- Simultaneously, loss of cyclable lithium occurs at both electrodes, as the SEI grows at the carbon anode as a result of electrolyte oxidation and/or changes in the oxide surface structure [31].
- The formation and growth of the SEI leads to gradual contact losses within the composite anode and thus increases the impedance in the cell [30].
- The loss of active electrode materials occurs, involving material dissolution, structural degradation, particle isolation, and electrode decomposition [32].

With regard to battery performance, both the loss of active materials and the loss of cyclability lead to capacity fade. Moreover, the increase in the battery resistance can be directly associated with power fade. A representation of all relevant aging mechanisms is illustrated in Fig. 4, and a more detailed discussion of the aging mechanism can be found in a previous work [33].



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Fig. 4. Degradation of Li-ion batteries; Christoph Birkel, 2014.

2.2.2. Origin of aging

As a general rule, two aging mechanisms are often distinguished: calendar aging and cycle aging. Each term refers to the changes caused by different uses of the battery.

2.2.2.1. Calendar aging. Calendar aging occurs while the cell is in storage. In other words, it is the irreversible damage to the cell's capacity caused when the battery is not in use [14,23]. The main stipulations regarding calendar aging are the storage temperature [34] and the (SOC) [35].

When the temperature is high, side reactions such as metal dissolution are more rapid and the loss of capacity is more marked than under ambient-temperature conditions [36–38].

The other main variable in calendar aging studies is the SOC level during storage [35]. Generally, the SOC represents the quantity of lithium ions present on the electrodes; this suggests, for a high SOC, a massive potential loss of cyclable lithium on the anode/electrolyte interface due to continuous SEI growth. Therefore, at the same temperature, cells age differently for different SOC levels. For example, an elevated SOC results in higher battery degradation [39].

In addition, because of the SOC dependence of the electrodes (self-discharge), several studies have focused on testing the calendar life of a cell under a constant applied voltage. Applying a constant potential is called “float charging,” and the results, of course, show an acceleration in cell degradation [13].

2.2.2.2. Cycle aging. Cycle aging occurs as the cell is operating, either charging or discharging. All issues previously described that influence the calendar aging are also included in studies of the cycle aging: the initial SOC [40,41] or temperature conditions [42]. In most cases, high temperatures will cause even greater charge capacity loss and impedance rise than those observed at ambient temperatures because of amplified aging effects [42]. In addition, it is crucial to account for the effects of very low temperatures [43]. The principal aging effect occurring at such temperatures is the plating of metallic lithium on the anode which is responsible for the loss of active material and growth of the SEI under cold conditions. This phenomenon will be described in the next subsection. The initial SOC is an important factor as it can yield to very fast aging. In [41], two Li-ion cells were cycled at 11 following initial SOC levels: from 10% to 100%. They found that with increasing cycle number, increase of the cathode's charge-transfer resistance was shown. This tendency is particularly present for a 10% SOC and a 100% SOC. Understandably, these increases in the charge-transfer resistance imply an ideal working SOC not too elevated or too low.

Besides such factors, the utilization mode of the battery is also an influencing function in cycle aging and it can be interpreted in different ways: charging/discharging current rate, depth-of-discharge, state-of-charge variation, charging/discharging voltage limit.

The current scale is known to play a significant role in cycle aging. Indeed, a high current rate generates a high solicitation of the cell for a given discharged energy [44].

In addition, a frequent factor cited in the literature is the SOC variation during a cycle, also known as Δ SOC. Under dynamic conditions, Δ SOC (%) is the difference between the minimum SOC and the maximum SOC induced during cycle life testing. Bloom et al. [36] experimentally tested Li-ion cells at the same temperatures and initial SOC but diverse Δ SOCs. The results indicated a loss of battery power for high Δ SOC values. This finding was later confirmed by another study [45]. On that matter, the authors in [45] attributed the increase in resistance and the power fade resulting from Δ SOCs to the structural changes and a phase transition of the cathode material which can lead to a capacity fade [33].

Another factor influencing Li-ion battery aging is the depth of discharge (DOD) [46], which also represents also the cell's utilization mode in a manner complementary to the SOC. For example, an SOC of 80% corresponds to a DOD of 20%. According to [46], a high DOD implies accelerated aging phenomena. To validate this, Shim et al. [46] cycled a 12-cm² pouch-type Li-ion cell over different DODs, namely, 100% (completely discharged) and 70% (30% energy remaining in the cell), at room temperature to investigate the cycle performances. Fig. 5 shows that the capacity loss and power fade of the cells cycled over 100% DOD were considerably faster than those of the cell cycled over 70% DOD.

The charging/discharging voltage limit during the lifespan of a cell is also a function of the operation mode. Thus, a high charging voltage leads to accelerated aging phenomena [47], and a discharge voltage lower than the manufacturer recommendations also induces more rapid aging via augmentation of the cell's resistance [48].

2.2.3. Aging effect

Rationally, when a cell is below 0 °C, the aging mechanisms described above are slowed or not dominant. However, these conditions create another problem due to the high polarization of the anode: lithium plating. In [49], the authors provided an explanation of this mechanism. Based on measurements of pouch cells with reference electrodes, the authors revealed a negative polarization with respect to Li/Li⁺ in the low-temperature range. This polarization is close to the potential of lithium metal (100 mV), and therefore, under these conditions, metallic lithium is deposited on the anode surface (Fig. 6). Post-mortem studies of the pouch cells revealed that the anodes were indeed plated with gray metallic lithium. This lithium plating leads to capacity loss by interfering with the intercalation of lithium between the anode and electrolyte and a loss of lithium (electrolyte decomposition) [33], which leads to capacity loss and, in turn, dramatically affects the cell's lifetime.

In the case of low-temperature charging, the dendritic growth of metallic lithium has also been reported [50]. Dendrites can reach

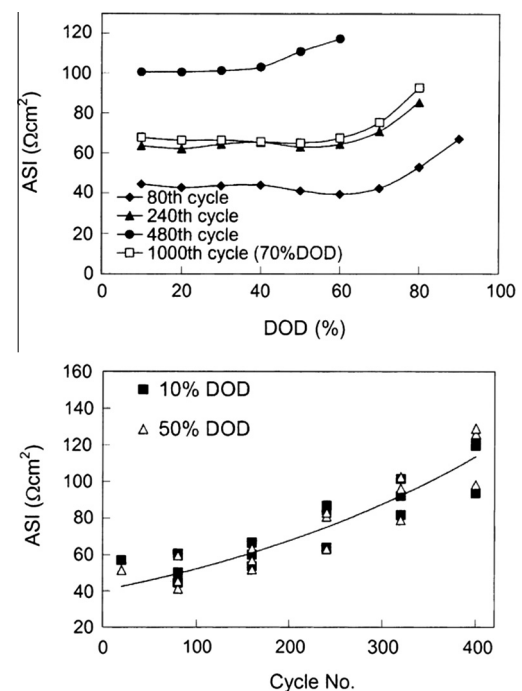


Fig. 5. Area-specific impedance result from [46].

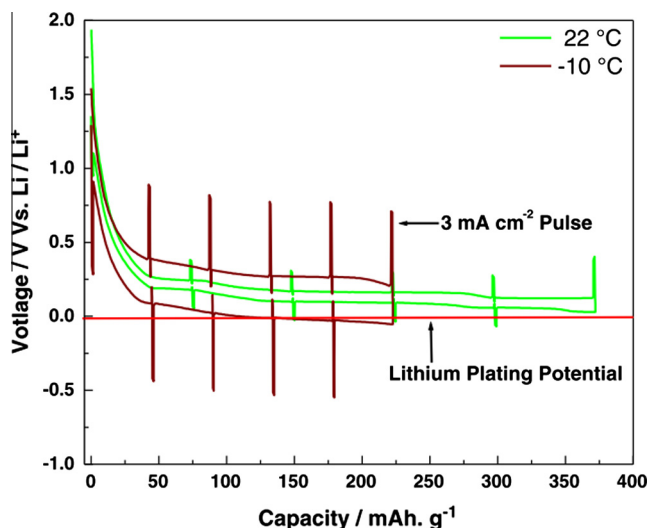


Fig. 6. Lithium plating phenomenon: the test conditions were a current density of 0.1 mA cm^{-2} followed by a pulse of 3.0 mA cm^{-2} with a duration of 6 s [12].

the positive electrode by penetrating the separator, which causes an internal soft shorting of the cell and poses a potential safety risk. They are a distinctive effect of lithium plating when a cell is nearly at the end of its life. Therefore, the mechanisms of metallic lithium plating and lithium dendrite growth must be considered as parasitic side reactions during charging.

Determining suitable means of charging Li-ion cells at low temperatures has become a task of major importance for automotive battery applications. In [51], an approach to understanding the lithium deposition reaction and predicting aging effects by extending an electrochemical model was proposed. The model parameterization involved data measured in the frequency domain using electrochemical impedance spectroscopy (EIS). The experimental cells were charged under different operating conditions: a wide range of temperatures ($T = -25^\circ\text{C}$ to 40°C) and currents ($I = 0.1 \text{ C}$ to 6 C). Capacity fade was gauged after a significant number of cycles and compared to the simulated anode potential. As expected, both high currents and low temperatures favor accelerated aging. More details of the developed electrochemical model will be explained in the next section.

Thus far, the principal solution to this lithium plating problem is to use anodes that operate at a higher working voltage vs. Li/Li^+ , such as lithium titanate, at the expense of energy density. The authors of [12] addressed the lithium plating mechanism from a different angle. To suppress the amount of lithium deposited at low temperatures, they altered the battery chemistry by applying different amounts of carbon coating (1,3-propanesultone) to the surface of natural graphite. This modification was achieved by uniformly coating carbon onto graphite via chemical vapor deposition (CVD). The results showed that at -10°C , carbon coating covering the entire graphite surface eliminates unwanted active points on the graphite and allows an optimized SEI layer to form. As a result, carbon coating of graphite is very effective in improving the safety of lithium batteries.

In conclusion, studies of Li-ion cells at low temperatures have indicated a need for the establishment of sophisticated model-based battery thermal management strategies, especially when used in electric vehicles. Indeed, to ensure optimal operation regarding operation limits, performance, and maximum lifetime, battery models are crucial for understanding internal processes, degradation effects, etc.

3. Modeling a Li-ion battery

3.1. General organization

Battery models are necessary to describe the features of the Li-ion battery. They are also the first step in the conceptualization of algorithms or management schemes for the implementation of a battery management system (BMS). They mathematically describe the parameters that influence the efficient use of the battery, such as voltage, load current, and temperature.

Modeling the dynamics of a vehicle battery system is essential in a BMS for monitoring, estimation, diagnosis, and control, but it is not a simple task because of the wide variety of working environments in vehicle applications.

Fig. 7 illustrates that for the design of a thermal strategy regarding batteries, a complete battery model requires good reproduction of three physical behaviors: electrical, thermal and aging. The models of these behaviors can also be characterized into three different types: electrochemical, empirical, and semi-empirical (electrical). Models in each category differ in their level of detail or their practical application but still reproduce experimental data such as voltage and charging time. In this paper, these battery models will be reviewed.

3.2. Electrical behavior

3.2.1. Electrochemical models

Lying at the interface of chemistry and physics, electrochemical models can be used to identify factors that limit cell performance. This type of model is the most accurate for optimizing aspect of physical battery design, but it is also the slowest in producing predictions (high computational demand). For instance, as shown in Fig. 8, Newman et al. [52] established an electrochemical model of discharge behavior using macroscopic parameters (e.g., battery voltage and current) and microscopic knowledge (e.g., concentration distribution). Song and Evans [53] adapted the Newman model by coupling an electrochemical and a thermal model to study the heat transfer and thermal management of lithium polymer batteries. Because they are completely physical, electrochemical models are extremely valuable for gaining a deep understanding of the behavior of electrochemical cells [54–56]. They yield important calculations and are commonly used for design and optimization processes.

For example, in [57], Omar et al. presented a three-dimensional (3D) model of large LiFePO_4 pouch cells. Validated using experimental

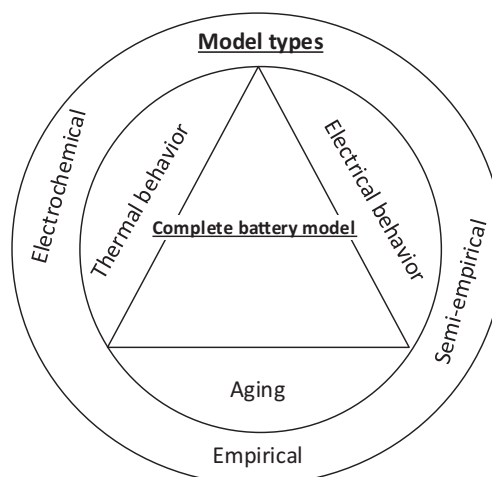


Fig. 7. Battery modeling schemes.

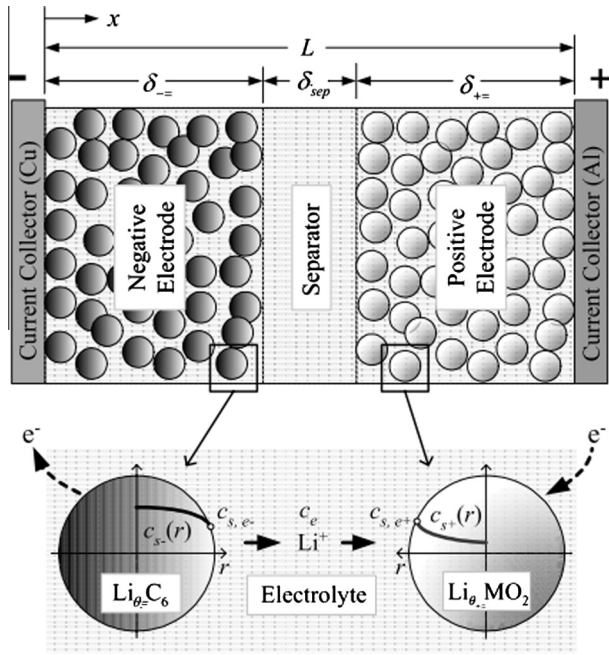


Fig. 8. Schematic of a Li-ion battery during discharge [52].

data, the coupled electrochemical-thermal model produced accurate simulations with fundamental details such as temperature non-uniformities, the potential distribution and the current density. Using this detailed model, they investigated the impact of the collector tab location on the variations in current density, potential, and heat. Various tab configurations were tested, and they concluded that symmetrical configurations tend to yield uniform distributions of potential current density and temperature across the cell surface.

Following the same approach, in [56], Omar et al. used a similar electrochemical technique to model the thermal behavior of an unbalanced battery module. The module consisted of 10 cylindrical cells with a nominal capacity of 18 Ah. In their investigation, the authors also varied the initial DOD of the module: 5%, 10% and 20%. Simulations of the temperature distributions inside the cells and the module were performed during discharging of the cells at constant currents of 18 A, 54 A, and 90 A. Their results demonstrated that a high DOD and discharge rate led to higher total heat generation inside the cells. The major contribution of this investigation is that using an electrochemical-thermal approach, the temperature distribution in each cell could be simulated and observed in great detail. However, because they specify and simulate the electro-thermal phenomena inside a cell, electrochemical models employ lists of parameters that must usually be acquired through data exploration, which can be time-consuming.

3.2.2. Empirical model

When an electrochemical model cannot be used, an empirical model is created instead because it simply consists of general equations representing the battery behavior with parameters suited to match experimental data. The first and simplest empirical model is Peukert's equation [58], which describes the nonlinear relation between a battery's capacity and the rate at which it is discharged:

$$C_p = I^k \cdot t \quad (3)$$

where C_p is the capacity, I is the discharge current, the empirical parameter k is the Peukert constant, and t is the discharging time. In [59], a statistical method was presented for modeling the discharge behavior of a Li-ion cell. In [60], Pedram and Wu proposed

a battery efficiency factor model based on empirical equations to predict the variation in capacity for different discharging current profiles with different probabilities. Empirical models are relatively cheap in both time and data. They are mainly descriptive and simple to configure, but their computational results are the least accurate, and they provide no knowledge regarding the real structure of the model.

3.2.3. Electrical model

Electrical models reproduce a battery's behavior by means of a simple electrical circuit. They use passive components such as impedances, polarization resistances, and capacitances as well as active elements such as controlled battery sources. Because this is a parametric approach, it can be used to model any battery, regardless of its chemistry, configuration, and rate of discharge, given a suitable combination of parameters. Therefore, electrical models are the most commonly employed for EV/HEV applications. Many such electrical circuit models are available in the literature [61–66]; an example of a simple electrical circuit is shown in Fig. 9.

3.3. Thermal behavior

All of the challenges facing the cold-temperature operation of EVs/HEVs are linked to thermal effects on the battery system: low performances, voltage drop, etc. Therefore, a proper means of establishing a new strategy for battery thermal management begins with the establishment of a detailed thermal battery model. The types of battery models described above offer various choices depending on the level of complexity, the design, the temperature monitoring and the control process. This sub-section will review the progress achieved in the thermal modeling of battery systems at low temperatures.

Currently, various thermal models are being introduced and studied in the context of cold-temperature HEV applications. In the early 80s, Bernardi et al. [67] developed the following general heat rejection equation:

$$q = I \left(U - V - T \frac{dU}{dT} \right) \quad (4)$$

where q is the heat generation rate (W), I is the current (A), T is the temperature (K), U is the OCV (V), and V is the working voltage (V) of the component (cell, pack, etc.). Based on Eq. (1), Pals and Newman [68] suggested a one-dimensional (1D) model to predict the temperature of single battery cell as follows:

$$V \cdot \rho \cdot C_p \frac{dT}{dt} = -h_s \cdot A \cdot (T - T_s) + q \quad (5)$$

where C_p is the heat capacity of the cell (J/kg/K), h_s is the heat transfer coefficient (W/m²/K), A is the battery surface area (m²), T_s is the environmental temperature (K), ρ is the density of the cell (kg/m³), V is the volume of the cell (m³), and q is the heat generation rate (W). In 2000, Hallaj et al. [69] proposed an updated 1D form of (4) for Li-ion batteries.

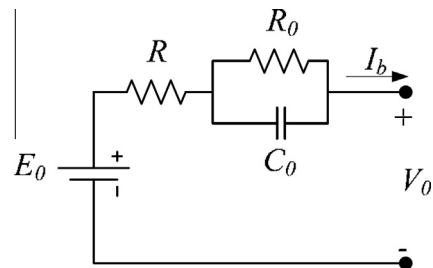


Fig. 9. Thevenin battery model [56].

In [70], Gu and Wang proposed an electro-chemical model combined with a thermal model on the micro-macroscopic level to assess both the electrochemical processes and the temperature inside a cell at low temperatures. Based on (3), in [71], a 3D electro-thermal cell model was developed to predict the electrical and thermal behavior of a Li-ion polymer cell.

In the same way, in [72], the authors adopted a thermal model based on [70] and compared the simulation results with their own experimental data obtained at different discharge rates and temperatures; the effects of the operating condition on the battery thermal performance were also included.

In addition, based on equations (4) and (5), several other authors have proposed various physical thermal models [73–75]. In these works, the thermal models are coupled with other heat generation equations related to chemical reactions, entropy or activation heat to predict the thermal behavior under certain conditions. An example of a geometric electrochemical model is depicted in Fig. 10.

As a final example of an electrochemical model, Omar et al. developed a two-dimensional (2D) thermal model to predict the temperature distribution inside a 45-Ah LFP/graphite pouch cell [76]. The thermal model involves solving a heat diffusion problem using an ANSYS FLUENT software interface. The input parameters are the heat generation and thermal properties. By virtue of numerous equations, the thermal runaway was studied in detail for different current solicitations and temperatures (0 °C, 2 °C, 10 °C, 15 °C, and 30 °C).

The electrochemical approach enables profound insight into non-measurable cell characteristics such as the electrolyte conductivity, the thickness of the electrode foil, or the radial distance between two Li particles. One means of obtaining these parameters is through rigorous data exploration, which is usually highly costly in material and time. A different approach allows the estimation of thermal behavior models at another level of complexity: via electrical modeling. Indeed, methods based on equivalent circuit models are generally employed for thermal behavior estimation. The experimental results of discharging tests of a Li-ion battery at a low temperature (−20 °C) reported in [18] reveal an important interaction between electrical and thermal phenomena. At −20 °C and 100 A, the high impedance of the cell decreased the cell's voltage and also produced heat through Joule heating, resulting in a final cell temperature of −5.6 °C. Hence, emphasizing the link between the heat production represented by Joule's first law and the voltage drop, represented by the Ohm's law.

In [77,78], the authors chose to ignore the effect of temperature on the internal resistance and formulated a temperature-dependent OCV. Moreover, the electrical terms of a Li-ion battery model including charge depletion, battery capacity, and thermal effects were taken into account. Regarding the thermal behavior, as shown in Fig. 11, this model separates the cell into two entities: a core and a crust. The temperature variations in the core and crust of each individual cell are then represented using convective and conductive heat-transfer terms.

Other thermal models for cold-temperature operation have also been proposed [79–81]. Saw and Tay presented a battery model capable of reproducing the I–V characteristics and thermal response of a battery as well as predicting its SOC [78]. The battery model consists of three RC blocks, one series resistor, and one voltage source. The parameters of the battery model were extracted from pulse discharge curves acquired at different temperatures (5 °C, 25 °C, and 40 °C).

In [79], Erdinc et al. captured the characteristics of real-life batteries in a MATLAB/Simulink® model developed based on several recent studies [82] to investigate the output characteristics of Li-ion batteries. Simulations were performed, including the variation of the battery output voltage at different currents and temperatures. The authors extended their work to the analysis of the aging rate of a Li-ion battery cell due to cycling. The simulation results were compared with experimental values obtained for various discharging currents (0.1 A, 0.5 A, and 1 A) at various temperatures (−20 °C, 0 °C, 25 °C, and 45 °C).

Finally, Omar et al. proposed a new second-order electrical battery model for Li-ion batteries operating at low temperatures (0 °C) [83]. Simply by adding the hysteresis effect to the electrical model, Omar improved several existing electrical battery models (Thevenin, FreedomCar, and the Simple R model). From the comparison results, it is evident that this new battery model is more precise than previous models.

In [80], Watrin et al. presented a multiphysical battery pack model for pack charge estimation using an extended Kalman filter (EKF). The approach was experimentally validated using measurements performed at several temperatures (−45 °C and 25 °C).

In [81], Feng and Gooi proposed a model of a commercial Li-ion battery considering temperature prediction. The model uses an electrical approach and modified correction factors for improved precision. Both current and temperature dependencies are considered along with the internal resistance changes to improve the model precision. Furthermore, the thermodynamic description relies on an equation that includes the entropy changes:

$$m \cdot C_p \cdot \frac{dT}{dt} = I \cdot (OCV - V) + I \cdot T \cdot \frac{\partial OCV}{\partial T} + h \cdot A \cdot (T - T_{amb}) \quad (6)$$

where m is the battery mass (kg), A is the battery surface area (m²), OCV is the open circuit voltage (V), h is the cooling coefficient (W/m²/K) and T_{amb} is the ambient temperature (K). In the right side of the equation, the first term is the polarization heat, second term

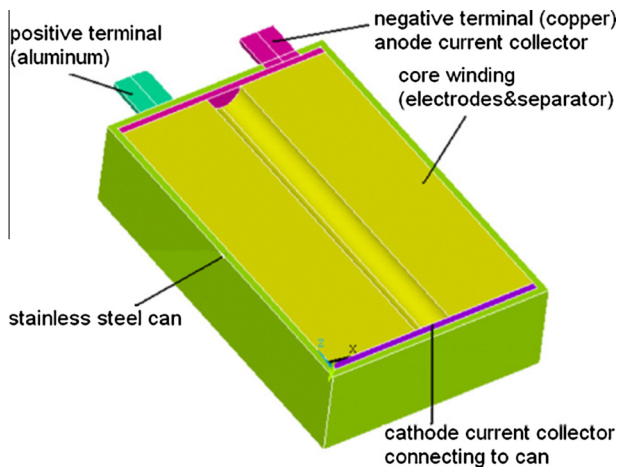


Fig. 10. Schematic of the 3D geometric electrochemical model [75].

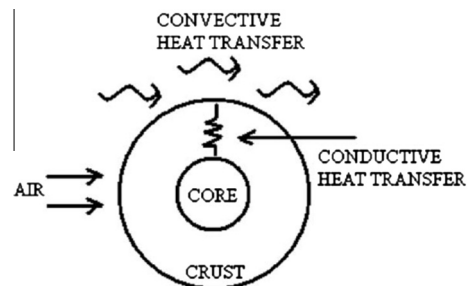


Fig. 11. Battery cell thermal model [77].

accounts for the entropic heat and the third term is the convective heat. The verification of model performance at different temperature conditions (-20°C , -10°C , 0°C , 23°C and 45°C) is accomplished and showed that it is able to predict the temperature. Likely to [77,84], the electrical model is a Thevenin-like model and the thermal dynamics are expressed in terms of the core and surface (crust) and rests on heat conduction between the core and surface, where m is the battery mass (kg), A is the battery surface area (m^2), E is the OCV (V), h is the cooling coefficient ($\text{W}/\text{m}^2/\text{M}$), and T_{amb} is the ambient temperature (K). On the right-hand side of the equation, the first term is the polarization heat, the second term accounts for the entropic heat, and the third term is the convective heat. The model performance was verified at various temperatures (-20°C , -10°C , 0°C , 23°C , and 45°C), showing it to be capable of successful temperature prediction. Similar to [77,84], the electrical model is a Thevenin-like model, and the thermal dynamics are expressed in terms of the core and surface (crust) and rely on the heat conduction between them.

3.4. Aging

For the assessment of aging, several concepts have not yet been implemented in BMSs to quantify the battery degradation level. Indeed, cell aging is a complex mechanism. Two principal changes are observed in a cell as it degrades: it loses capacity and its impedance increases. Many methods of quantifying these characteristics of aging have been reported in the literature. They can be classified into three types: electrochemical models, performance-based models, and equivalent-circuit-based models.

3.4.1. Electrochemical model

This type of modeling is regarded as fundamental or particle-based distribution modeling. Its aim is to provide a profound understanding of the physical and chemical phenomena occurring during battery operation. Such models are applied at the nanoscale using partial differential equations [85]. They offer a deeper perception of non-measurable cell parameters, for instance, using the anode potential as an indicator of metallic lithium deposition (lithium plating). The development of these models began approximately 20 years ago with the work of Newman's group [86,87], who sought methods of estimating battery performance based on the Butler–Volmer equation and porous electrode theory [88]. At present, most approaches focus on the effect of aging on the negative electrode.

More recently, in [51,89], Tippmann et al. developed a pseudo-2D electrochemical model to predict aging effects during charging. Indeed, a qualitative correspondence has been identified between the occurrence of lithium plating in experiments and the anode potential dropping below 0 V vs. Li/Li^+ .

3.4.2. Empirical model

An empirical model is built based on data obtained from experiments for the estimation of values. Such approaches are used to determine both model parameters and direct aging factors. The most well-known method is “Coulomb counting,” in which the health of the cell is evaluated by integrating the current over time [90]. The major disadvantage of this approach is the need for the Coulomb counting to be performed under the same conditions, such as external temperature, every time. In addition, it requires periodic recalibration and cannot be performed in real time [91].

As an alternative approach, artificial neural networks (ANNs) and neural networks (NNs) are commonly used to predict the SOC [92] of Li-ion batteries, as has previously been done for lead-acid batteries [93]. NNs can be easily adapted for comparisons to other battery technologies [94] and perform well despite multiple

dependences; however, like any iterative mechanism, NNs require a large amount of data to be effective.

In addition, empirical models are often used to target the estimation of another figure of merit of a battery: the state-of-health (SOH) [95,96]. The SOH is one of the most commonly used indicators in the literature, and it is generally defined as follows [40]:

$$\text{SOH} = \frac{C_{\text{dis,act}}}{C_{\text{dis,init}}} \quad (7)$$

where $C_{\text{dis,act}}$ is the actual discharge capacity of the battery (Ah) and $C_{\text{dis,init}}$ is the initial discharge capacity of the battery (Ah). Another SOH estimation method was introduced by Guo et al. in [97]. In this approach, charging test data from different stages of battery life are employed to measure the extent of capacity fade and to obtain a time-based parameter to enable SOH estimation. As another example, Long et al. [98] employed this method to construct a capacity fading model in which the capacity fade is treated as an estimation of the SOH. Alternatively, Kalman filters can also be used for SOH estimation [99,100].

Using a different approach, Singh et al. [101] determined the number of remaining cycles for a battery. Recent advances in spectroscopy have enabled the implementation of EIS in battery research as a new means of SOC/SOH estimation. In [101], the authors used EIS data for various battery SOC and cycle numbers to assess two input variables: the magnitude of the impedance and the phase angles. The extracted EIS data were used to establish accurate empirical models for evaluating both the cycle number and the SOC for a battery pack.

Finally, the EIS technique has also been demonstrated in the literature for SOH estimation. For example, Love et al. [102] described a single-point impedance measurement for assessing the damage to 18650 Li-ion batteries. Using EIS, they identified an SOH frequency of approximately 316 Hz, specific to their battery. An example of experimental data from this study is presented in Fig. 12. They defined this frequency as the point at which the impedance response of their cell exhibited the least variance over a range of SOC (from 0% to 100%). They concluded from their findings that this single-point impedance method could be used as an SOH indicator in a BMS.

3.4.3. Semi-empirical models

Semi-empirical models can be distinguished into two classes: performance degradation models and equivalent circuit models. Performance degradation models involve the online calculation and updating of stress factors and capacity fade/impedance rise. The principal method used to evaluate battery performance is to model the changes in the physical characteristics of the battery

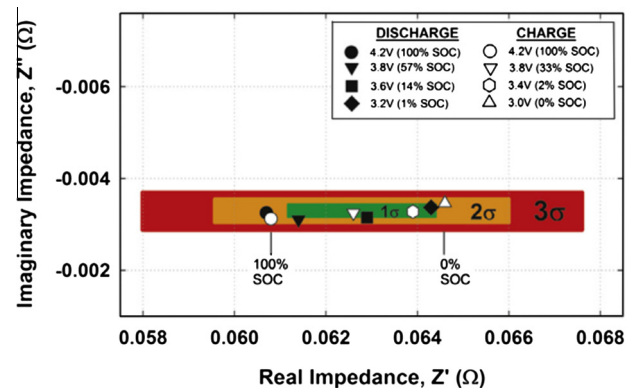


Fig. 12. SOH chart illustrating the change in impedance response collected at 316 Hz perturbation frequency with SOC [102].

components (electrodes, electrolyte) during the battery degradation process. Most studies address both types of aging processes: calendar and cycle [103]. Generally, both calendar and cycle aging appear to follow Arrhenius-like dynamics (8), as this law is typically applied for temperature considerations [11,36,104].

$$v = A \cdot \exp\left(\frac{-E_a}{RT}\right) \quad (8)$$

where v is the aging rate, A is the pre-exponential factor, E_a is the activation barrier (KJ/mol), R is the gas constant (J/mol/K), and T is the aging temperature (K). Although the Arrhenius law can be categorized as an empirical approach, it is primarily based on physical equations [105], and the estimation of the aging parameters (E_a , A) is performed through measurements; therefore, in this paper, we classify it as a semi-empirical approach. Furthermore, performance-based aging models are not only focused on the evolutions of capacity and impedance but also can be integrated into equivalent circuit models in an attempt to represent aging losses of both the cycle [106] and calendar [107] types.

Although it is not the most detailed battery model possible, an equivalent circuit model is often chosen because of its simplicity and ease of understanding. These qualities make such models attractive and widely used for model-based estimation techniques for EV/HEV applications. An equivalent circuit model representation encompasses an ideal voltage source, an internal resistance, and n parallel RC circuits, where n is the order of the model. All of the aforementioned parameters are considered to vary during battery degradation [108].

Generally, one method of estimating the aging rate is to assume Arrhenius-like behavior because of the simplicity of integrating this assumption into an equivalent circuit model [49,103]. Many researchers have fitted the aging rates of Li-ion batteries using Arrhenius' Eq. (6). In [109], the authors first demonstrated that capacity fades during calendar aging at an Arrhenius-like rate. In [36], the authors determined the activation barrier potentials, E_a , of Li-ion cells in several calendar aging tests, whereas in [110], the impact of aging on the state of energy was depicted and reproduced via Arrhenius theory.

However, the Arrhenius-like behavior considered in these studies is only valid in a certain temperature interval, which does not include all temperatures to which EVs/HEVs might be exposed during winter operations (below 0 °C). In general, it is claimed that low temperatures slow the aging rate. However, as shown in Fig. 13, a cold environment changes the slope of the Arrhenius plot, indicating a change in the relevant mechanism [11,111]. The authors of the cited studies attributed the negative activation barrier the lithium plating side reactions. However, the apparent

negative sign of the activation energy is thermodynamically incorrect [112].

In [11], Broussely et al. proposed a model that considers the capacity loss rate during accelerated calendar aging at high temperatures (Fig. 14). From this simple model, the corrosion rate was found to be time-dependent, proportional to $t^{1/2}$ [36,103,113]. Subsequently, numerous studies have adopted this law [114,115]. In [115], the authors performed aging tests on electrochemical double-layer capacitors (EDLCs). The main contribution of this study is that the data and statements made presented by the authors in [115] are also applicable to Li-ion batteries. As an EDLC ages, the characteristic changes in its impedance parameters follow the same pattern as those in Li-ion batteries, as they can be described as an increase in the internal impedance [116]. In addition, based on these aging tests, a generalized impedance model was developed. The model consists of a series inductance, a resistance, and a pore impedance. The evolution of the impedance parameters is described by a function that is linear with the conductance, emphasizing the possibility that the calendar aging rate follows a simple mathematical function. For example, Ecker et al. [116] proposed a calendar lifetime estimation model depicting the variations in capacity and resistance over time. Thomas and Bloom [113] developed a statistical model based on data from accelerated aging experiments and Monte Carlo simulations. In [36], Bloom et al. studied the accelerated calendar and cycle aging of Li-ion cells from the perspective of the increase in the area-specific impedance (ASI). The rates of the calendar ASI increase followed kinetics dependent on $t^{1/2}$. Bohlen and Kowal [115] obtained coefficient values from accelerated calendar aging data for an aging rate model with the following main equation:

$$a(t, T, V) = a_{init}(1 + c_a t_{eq}) \quad (9)$$

where t_{eq} is the equivalent aging time, defined as

$$t_{eq} = t \cdot C_T^{(T-T_0)/\Delta T} \cdot C_V^{(V-V_0)/\Delta V} \quad (10)$$

The constants T_0 , V_0 , ΔT , and ΔV can be chosen arbitrarily. T_0 and V_0 are the reference temperature and voltage, respectively; t_{eq} is the real time under nominal conditions; and c_a is the relative aging rate under nominal conditions. However, according to Liu et al. [117], the evolution of the capacity fade as a function of storage time and SOC depends on time proportional to $t^{0.75}$. The results obtained in this study reveal that the capacity fade varies according to a polynomial relationship. The authors ascribed the observation of a time exponent of 0.75 instead of 0.5 to the use of different Li-ion battery chemistries and operating conditions [118].

Regarding cycle aging, other aging models presented in the literature [37,103,119] exhibit a typical cycle number dependency

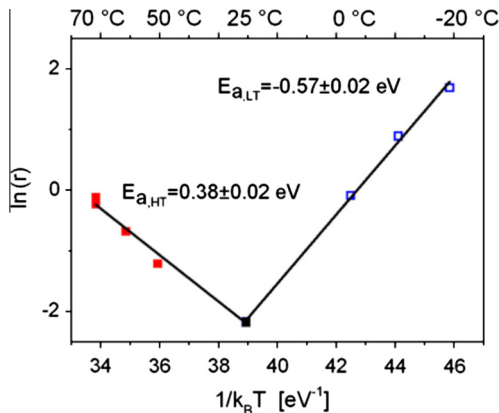


Fig. 13. Arrhenius plot of the aging behavior of 18,650 cells cycled at 1 C in a temperature range of –20 °C to 70 °C [49].

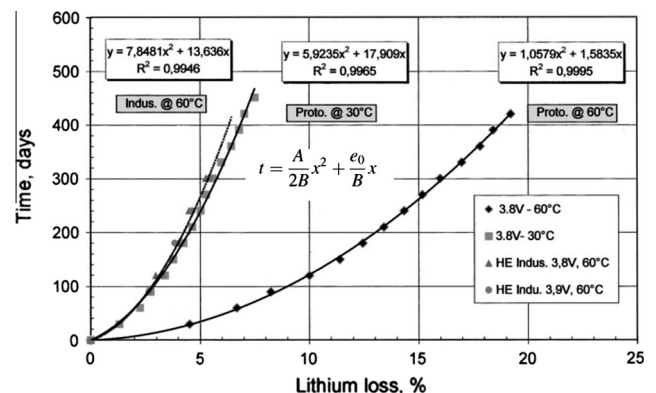


Fig. 14. Storage time as a function of lithium loss, consistent agreement with the corrosion law [11].

for cycle aging. They describe the growth of the SEI layer as a linear or other simple function of the cycle number. For instance, in [103], the authors proposed a typical cycle-number-dependent model. By contrast, in another study, each model parameter exhibited a cycle^{1/2} dependence [113]. In addition, Omar et al. proposed a cycle aging model for one particular Li-ion technology, that of the lithium iron phosphate cell (LFP) [40]. They developed a cycle-life model for LFP batteries with different aging parameters: current rates, working temperatures, and DODs. Through testing, they derived the impact of each of these parameters on the obtained mathematical expressions. Then, they developed a Simulink model based on these expressions, which, according to the results, can accurately predict the battery cycle life. In that paper [40], they not only proposed an aging model but also emphasized, via aging tests at low temperatures (−18 °C), that the Arrhenius law cannot be applied in this temperature range.

4. Thermal management strategies for Li-ion batteries

Li-ion cells, especially when used in EVs under varying operation conditions, require elaborate battery thermal management strategies to guarantee ideal operation in terms of performance and lifespan. This is achieved via a battery thermal management system (BTMS). A BTMS is composed of systems that may be either active (external or internal sources of heating and/or cooling) or passive (natural convection) and can also be categorized into systems based on air, liquid, and phase-change materials (PCMs).

4.1. Air management

As shown in Fig. 15, a battery pack is commonly configured with several cells in series in multiple rows [120]. Considering this battery pack layout, air cooling systems are commonly used in battery-powered vehicles because a cooling effect can be easily achieved by targeting the pack with a flow of air. Therefore, air management requires only simple equipment and little space compared with other strategies, such as liquid management [121]. Usually, there are two modes in which the air may flow over the battery (Fig. 15): in parallel or in series. Zolot et al. [122] first exploited a parallel airflow system in a Toyota Prius HEV to cool down the battery, and the results were satisfactory. Serial airflow remains relatively uncommon.

In addition to parallel and serial flow studies, the uniformity of temperature that can be achieved using air-cooling strategies for different battery pack arrangements was also investigated in [123] by placing fans in different locations with respect to the battery pack. The conclusions were that the best cooling performance is achieved when the fan is on top of the pack and that the most

interesting layout in terms of cooling effect and cost is a cubic arrangement (i.e., the same numbers of cells along both the length and width of the pack). Forced-air convection cooling can therefore moderate the temperature increase inside a battery pack.

However, Nelson has demonstrated that past a certain temperature point (66 °C), it is difficult to cool a battery via air cooling because of the low conductivity of air [124]. Thus, at reasonable discharge rates and operating temperatures (<60 °C), air cooling is advised [125], whereas under harsh and demanding conditions (>60 °C), a liquid system is preferable.

4.2. Liquid management

Liquid cooling/heating for battery packs can be achieved using two different approaches: surrounding the modules with a jacket/plate containing streams of heated/cooled liquid or immersing the modules in direct contact with a cooling/heating fluid [126,127]. The heat transfer liquid could be water, oil, acetone, glycol, or even a refrigerant. In [126,128], Pesaran compared liquid cooling with air cooling. Based on his observations, he suggested that air-based systems are less difficult to set up but less efficient than a system using liquid cooling/heating.

Zhao et al. demonstrated a cooling method for cylindrical batteries based on a liquid-cooled cylinder [129]. The objective of their method is to maintain the maximum temperature of the pack within an ideal temperature range (25 °C) and ensure small local temperature differences between cells. The variables in their study were the mass flow rate, the flow direction, and the size of the entrance to the heat dissipation device. The maximum temperature was successfully controlled below 40 °C for cylindrical batteries using a flow rate of 10^{−3} kg/s. Based on these results, the authors demonstrated the advantages of a liquid cooling configuration compared with natural convection systems, for example.

In [130], the authors studied the temperature distribution in a stack with liquid heating. The tests were performed on a 20-Ah flat battery stack, and numerous variables were considered, such as ambient temperature, Reynolds number, and discharge rate. The simulation results indicated that liquid cooling is generally more efficient than the PCM strategy, although PCMs engender a more uniform temperature behavior. Surprisingly, the authors observed no significant influence of the Reynolds number in the case of liquid cooling, but only in the air-cooling case.

Another method involves using heat pipes instead of circulating water. First proposed by Gaugler in 1942, heat pipes have received increasing attention in recent years. A heat pipe consists of a sealed container filled with a working fluid. The working fluid is a saturated liquid that vaporizes and travels to the condenser, where it is cooled and turned back into a saturated liquid. The condensed

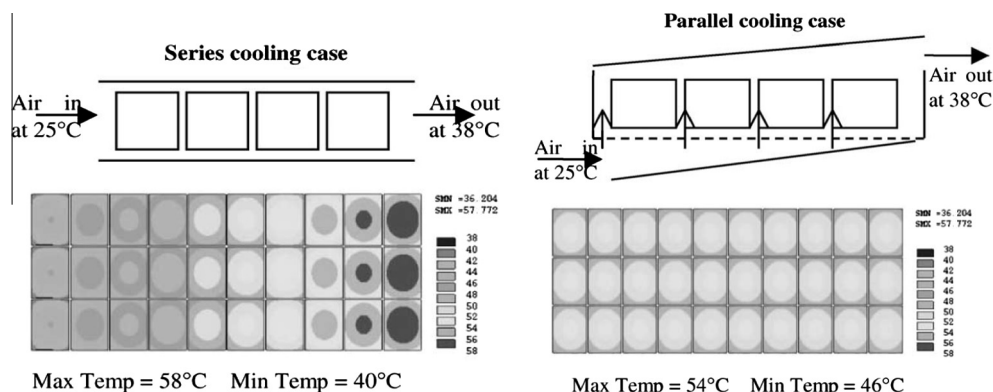


Fig. 15. Battery packs (squares) with serial and parallel cooling system [141].

liquid is returned to the evaporator via the capillary process acting on the liquid phase.

In the study reported in [131], the authors equipped a real vehicle with a heat-pipe-based thermal management system to increase the cycle lifetime of the battery and reduce the general cost of EVs. The experimental results showed that the temperature of the pack could be regulated below 50 °C while driving, corresponding to a heat generation rate lower than 50 W. Thus, as they concluded, applying heat pipes in battery-based vehicles is an effective method of saving energy in EVs.

In addition, Jang and Rhi [132] proposed the heat-pipe cooling approach presented in Fig. 16. The system combines heat-pipe and air cooling. The heating section of the heat pipe is placed on the surface of the battery, and a fan blows air over the cooling section of the heat pipe. Their experiment showed that with 50 W of heat, this system dissipates heat such that the temperature of each cell is maintained below 50 °C. Moreover, the working temperature was less than 50 °C when pure water was used as the heat-pipe fluid and 45 °C in the case of acetone.

4.3. Phase-change materials

BTMSs based on liquid cooling and air cooling are often large, convoluted, and costly in terms of air vents, fans, pipes, pumps,

etc. [133]. Hence, other thermal management solutions are required. An innovative solution for EV/HEV applications has been suggested: the use of PCMs. A PCM is a substance capable of storing and releasing large amounts of energy (heat) at a given temperature as a result of its melting and solidification. Heat is liberated or absorbed as the substance changes from solid to liquid and vice versa. When first proposed by Al-Hallaj and Selman [134], PCMs actually performed better than “traditional” thermal management systems, but their development was still in the experimental phase. In [135], the authors extended the previous work on PCMs. They reviewed 740 PCMs sorted by material category to inform an evaluation of all possible available PCMs. Fig. 17 shows the large number of materials surveyed in [135].

In addition, Selman and Al-Hallaj [136] tested various modes of thermal management, including PCMs, on a Li-ion battery designed for an electric scooter application. In their experiment, the PCM strategy yielded the most satisfactory effect compared with the other approaches. Along the same lines, Kizilel et al. [137] confirmed the usefulness of PCMs by demonstrating that uniform temperature in a module is achievable using a PCM system regardless of whether it is under normal or stressed conditions. The benefits of using PCMs compared with active liquid cooling were demonstrated on an 18650-cell module.

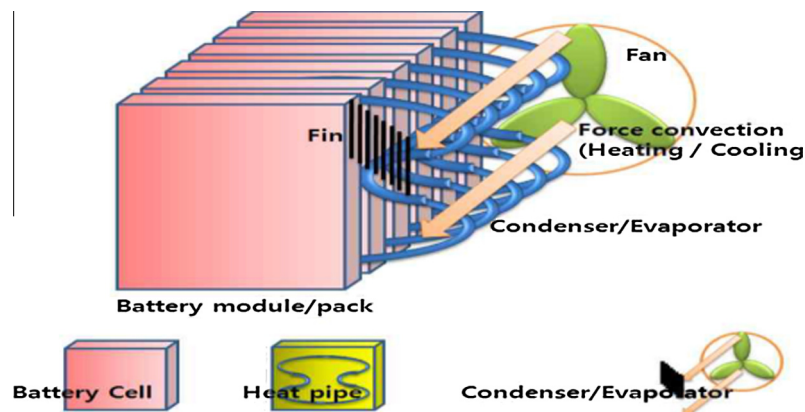


Fig. 16. Heat pipe battery cooling system [132].

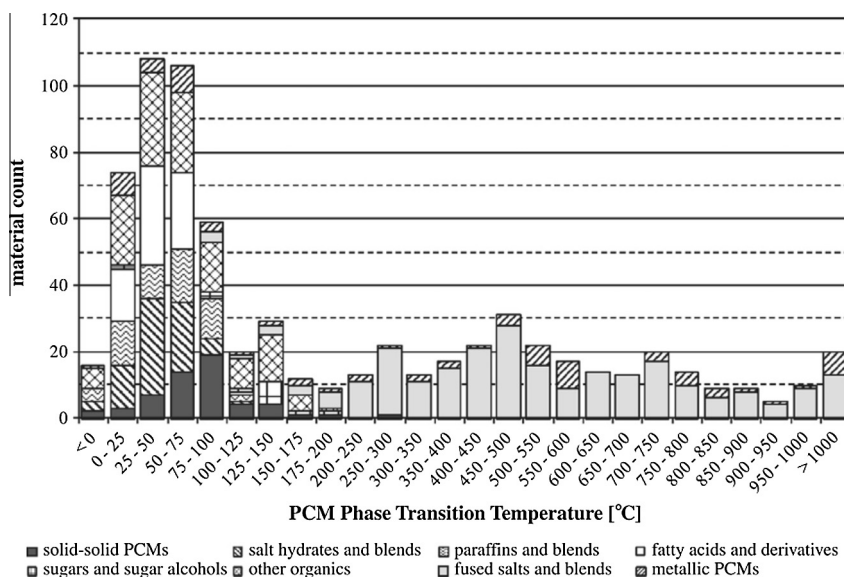


Fig. 17. Transition temperature distribution of 740 PCM candidates, sorted by material category [135].

4.4. Heating strategies

According to the analyses presented above in Sections 2 and 3, two main problems are encountered at low temperatures. The first is the slowing of mechanisms occurring inside the cell, which engenders a general drop in performance measures such as the available capacity. The second is that charging a cold Li-ion battery leads to the plating of metallic lithium onto the anode, which enlarges the SEI and accelerates degradation. To prevent this from occurring, the solution is simple; the battery must be heated using an efficient heating strategy.

4.4.1. Air management

Surprisingly, the first heating strategy to be considered for use in cold weather was air heating. In [15], Song et al. addressed this issue for cold start-up applications using an experimental battery and an atmospheric simulation system. The idea was to pre-heat the battery using an external air-heating strategy in a real cold-weather scenario and compare the results with those for a bare battery. The experimental results indicated that a battery retains greater capacity if the area surrounding the battery is warmed to ambient temperature before start-up.

Regarding heating strategies, Ji and Wang [14] presented and compared different strategies from two perspectives: external and internal sources. They studied external air heating and reported that external convective heating using a fan and a heater requires the least heating time, although it is a more sophisticated approach. Examples of external air heating are depicted in Fig. 18.

4.4.2. Liquid management

Liquid heating offers better thermal conductivity and a higher convective heat-transfer rate than air heating, but it requires a

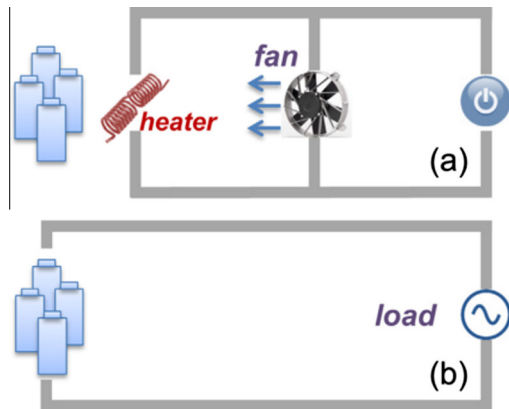


Fig. 18. Heating strategies using: external power (a) and alternative current (b) [14].

more complex heating system. Nevertheless, liquid heating is commonly used in EVs/HEVs. For example, in the Chevrolet Volt, the coolant water circuit streaming around the pack is heated by 360-V electrical heaters [138]. Temperature sensors calculate the required current to apply to the high-voltage electrical heaters.

Alternatively, in [139], Henao et al. proposed a cold start-up strategy for a proton-exchange-membrane fuel cell (PEMFC) with an antifreeze fluid (a mixture of glycol and water) as a heating fluid. The time required to warm the system using the proposed methodology was satisfactory, and the fuel-cell stack temperature increased rapidly. The heat transferred by the heating fluid was represented by commonly used thermal equations taken from the literature [112]. Therefore, this method developed for PEMFCs could also be adapted for battery packs.

4.4.3. Phase-change materials

For low-temperature operations, PCMs can also be used as heating materials. Indeed, if the battery temperature drops below the melting point of the PCM, the heat stored by the PCM is released to the battery pack. In fact, in [134], the authors foresaw that PCMs would offer a major advantage for EV operation under cold conditions or in space applications, in which the battery temperature drops precipitously.

4.4.4. Alternative current heating

In contrast to external heating, another method has been established for heating HEVs. It consists of internal heating using alternating current (AC) [140]. All of the external heating methods presented above add considerable weight and cost. In 2004, Stuart and Hande [140] proposed warming the battery directly with an AC current rather than using external heaters, relying solely on internal losses (Joule heating) proportional to RI^2 . Several tests were performed at different SOC, using different battery technologies (lead/acid and NiMH) and at different temperatures (-20°C to -40°C). These tests showed that at current amplitudes of 60–80 A (high), the battery heats very rapidly for both technologies. However, the influence of the sign or frequency on the heating rate had not yet been demonstrated.

Finally, to further pursue this study, Jin and Wang [14] simulated AC heating at different frequencies (from 0.01 Hz to 2 kHz). They compared their results against existing external heating strategies and found that AC heating is preferred because it heats the cell more uniformly and creates little temperature difference inside the cell.

4.4.5. Conclusion

In 2004, Cosley and Garcia [141] evaluated the state of the art of BTMSs. Based on research from recent years, an updated analysis of all investigated battery thermal management strategies was presented in [126,142,143], and it is summarized in Table 1.

Table 1

Trade-off analysis for the actual battery thermal management.

	Forced air	Liquid	Heat pipe	PCM	Thermoelectric	Cold plate
Ease of use	Easy	Difficult	Moderate	Easy	Moderate	Moderate
Integration	Easy	Difficult	Moderate	Easy	Moderate	Moderate
Efficiency	Low	High	High	High	Low	Medium
Temperature drop	Small	Large	Large	Large	Medium	Medium
Temperature distribution	Uneven	Even	Moderate	Even	Moderate	Moderate
Maintenance	Easy	Difficult	Moderate	Easy	Difficult	Moderate
Life	>20 years	3–5 years	>20 years	>20 years	1–3 years	>20 years
Initial cost	Low	High	High	Moderate	High	High
Annual cost	Low	High	Moderate	Low	High	Moderate

5. Conclusion

In this paper, a brief review of the effects of cold temperatures on Li-ion batteries is presented. This review illustrates why Li-ion batteries are currently regarded as the best choice for clean vehicle applications. However, this technology faces two major problems with regard to low-temperature operation: performance loss and degradation. These hindrances have slowed the expansion of the EV market, particularly in cold-weather countries. Therefore, an ideal thermal management system is necessary to address these harmful actualities. Indeed, a battery thermal system should be able to maintain a battery pack at an optimum temperature.

A quick search shows that most thermal strategies begin with the elaboration of an efficient battery model. Various kinds of models are discussed in this paper with different levels of computational complexity and accuracy; they can be categorized as electrochemical, empirical, and electrical models.

Various methods of addressing aging effects are also considered in this review; these methods attempt to reproduce such phenomena using approaches ranging from empirical and semi-empirical perspectives to more data-analysis-oriented studies (electrochemical models).

Finally, particular focus is placed in this review on traditional methods of battery thermal energy management, such as air cooling, liquid cooling, and PCMs, with all their advantages and disadvantages.

Nevertheless, the challenges that hinder the market penetration of HEVs/VEs in cold-weather countries must be resolved, and methods of detecting lithium plating should be applied in BMSS.

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