Journal of Power Sources 400 (2018) 621–640

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Review article

Selection of thermal management system for modular battery packs of electric vehicles: A review of existing and emerging technologies

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HIGHLIGHTS

- Effect of temperature on performance and safety of Li-ion battery is discussed.
- Recent developments in state-of-the-art thermal management methods are summarised.
- Alternatives for traditional thermal management techniques are presented.
- Suitable candidates for modular thermal management system are identified.

ARTICLE INFO

Keywords:
Phase change materials
Magnetic refrigeration
Thermoelectric and thermo-acoustic battery thermal management systems
Heat pipes
Cold plates
Solid electrolyte interphase film

ABSTRACT

Li-ion battery cells are temperature sensitive devices. Their performance and cycle life are compromised under extreme ambient environment. Efficient regulation of cell temperature is, therefore, a pre-requisite for safe and reliable battery operation. In addition, modularity-in-design of battery packs is required to offset high manufacturing costs of electric vehicles (EVs). However, modularity of battery packs is restricted by flexibility of traditionally used battery thermal management systems. For example, scalability of liquid cooled battery packs is limited by plumbing or piping and the auxiliary equipment used in the system. An alternative thermal management system is, therefore, required for modular EV battery packs.

In this paper, state-of-the-art developed to control battery temperature near a pre-specified state is qualitatively reviewed with the intent to identify potential candidate for implementation in a modular architecture. Some of the novel techniques that provide high-scalability in addition to appreciable cost and energy-savings over traditional methods are also evaluated while considering the development state and associated technical risks. It is found that only a hybrid system can meet technical requirements imposed by modular design. Based on the current state, phase change materials and thermoelectric devices are more likely to be part of this next generation thermal management system.

1. Introduction

Various chemical reactions and electrochemical transport phenomena characterise the normal charging and discharging processes in a battery cell. Many of these reactions are exothermic in nature [1], meaning that temperature affects the performance of a battery pack. General Motors estimated that if an electric vehicle (EV) is operating in sub-zero temperatures, its driving range can be reduced by several percent due to the sluggish charge kinetics in the battery cells [2]. On the other hand, if heat transfer from the battery pack to the external environment is not sufficient, excess heat may accumulate in the battery pack, particularly when it is being operated in a hot climate or under an insulating environment [3]. Hot spots can also develop, leading to an uneven temperature distribution across the battery pack, which can alter charging and discharging characteristics of the battery cells [4,5]. More importantly, the battery cell temperature may rise beyond the safety limits of 60 °C for Li-ion battery cells using $LiBF_4$ as electrolyte, risking battery pack failure [6].

Previous studies indicate that the battery cell temperature must be regulated within a predefined operating range to sustain a rate of reaction considered healthy for the efficient operation of battery cells. The recommended operational range for Li-ion battery cells is generally between 25 °C and 40 °C [7,8]. Managing large temperature spikes and non-uniform thermal gradients across the battery pack is, therefore, a major concern in the design of large battery packs essential for supporting an EV driveline. For these reasons, a battery thermal

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https://doi.org/10.1016/j.jpowsour.2018.08.020
Received 7 March 2018; Received in revised form 3 July 2018; Accepted 8 August 2018

Table 1
List of OEMs distinguishing those which prefer to use a thermal management system for their EV battery packs from those which do not (*Mitsubishi iMiEV offers a variant with forced air-cooled battery pack, i.e. there is an optional fan that can be attached to its battery back for limiting the temperature rise during fast charging operations).

OEMs not using TMS	OEMs using TMS
Nissan	Tesla
BYD	General Motors
Volkswagen	Ford
Mitsubishi	Mercedes
Renault	Fiat

management system (TMS) needs to be integrated with the EV battery pack, although the original equipment manufacturers (OEMs) have followed different approaches [9]. Table 1 separates the OEMs that are in favour of using a TMS from those who do not use it.

Several incidents involving battery cells overheating and catching fire have been reported to date. In many cases, the problem of battery overheating has caused OEMs to question the reliability of battery packs and loss of markets for battery-powered products. A list of major product recalls and incidents of battery-powered products catching fire in recent history is available from Ref. [10].

It is evident that thermal stability is a major issue for Li-ion battery packs. In addition, the high manufacturing costs of battery packs hinder the marketability of EVs. Mass-market appeal of EVs can be improved by using economies of scale generated by the implementation of modular battery pack architecture. However, the concepts of mechanical and thermal modularity are inter-connected. The thermal independence of each battery cell must be ensured to preserve their interchangeability [11]. In this paper, different thermal management techniques that can be applied for the regulation of the thermal behaviour of Li-ion battery packs are qualitatively reviewed to ascertain their suitability for potential implementation in a modular system. In order to provide more context for this work, the paper first presents a simplified overview of the main issues affecting behaviour of the Li-ion battery cells in low/elevated ambient temperatures.

2. Effect of temperature on Li-ion battery cells

Li-ion battery cells belong to a category of temperature-sensitive devices, since both their performance and their safety are influenced by their operating temperature [12]. Research has shown that commercial Li-ion battery cells achieve optimum performance near room temperature [13]. This section discusses various challenges associated with operating Li-ion battery cells in temperatures that are far from this ideal condition.

2.1. Effect of low temperature

It has been reported that *18650* type Li-ion battery cells can supply only 5% and 1.25% of the energy capacity and power capacity available at 20 °C, respectively, in low operating temperatures such as −40 °C [14]. Similarly, the driving range of the 2012 Nissan LEAF has been noted to drop substantially from 138 miles in ideal conditions to 63 miles at −10 °C. Moreover, information presented by different research groups [14–16] on the energy capacity of Li-ion batteries available during constant current discharge/charge tests conducted in low temperatures confirms that the usable battery capacity decreases as the operating temperature is reduced.

It was previously believed that the unsatisfactory performance of Li-ion battery cells at low temperatures was due to their limited electrolyte conductivity, which affects the Li-ion transportation rate between the two electrodes at these temperatures. However, further investigations suggest that inadequate electrode activity can also cause poor low temperature performance in Li-ion battery cells. Electrode activity refers to the combined effect of marginalised Li-ion transfer through surface films on Li-ion battery cell electrodes called the solid electrolyte interphase (SEI), and the high charge-transfer resistance and slow diffusivity of Li-ions within the anode materials [17–21].

Of the control factors [22,23], the choice of electrolyte for Li-ion cells is critical to the improvement of their low-temperature performance, primarily because of the intrinsic loss of ionic conductivity associated with low operating temperatures. In addition, SEI film's chemical composition and physical characteristics, such as its resistance and conformability to Li intercalation, depend on the salt forming the electrolyte, and parameters such as the quality of the anode material, and the mode and temperature of the SEI formation [24,25]. SEI is a surface film approximately 5 Å to 800 Å thick, consisting of both organic and inorganic compounds, which keeps the electrolyte kinetically stable at anode potentials of less than 0.8 V. The thickness of the film varies with the degree of anode graphitisation [26,27]. Interestingly, this anodic film is highly resistive and interferes with the Li-ion transport kinetics at the electrolyte/electrode interphase [28]. Most research activities to date have therefore focussed on improving the conductivity and stability of electrolytes with effective SEI film formation. Approaches that have been central to this improvement are:

1. Use of co-solvents with low viscosity and low freezing temperatures, such as glymes, esters and lactones [29–31].
2. Formulation of new additives for electrolytes to further lower their freezing point [32–35].
3. Substitution of the existing lithium salt $LiPF_6$ with new mixtures to improve the charge transfer resistance and other characteristics of the SEI film [36–40].

2.2. Effect of elevated temperatures

United States Advanced Battery Consortium (USABC) has defined a performance target of 15 years' calendar life for all the battery packs to be used in HEVs, while the targeted calendar life for EV battery packs is 10 years [41]. It is, therefore, of utmost concern that elevated temperatures, i.e. temperatures greater than 40 °C, accelerate the battery ageing phenomena. Battery ageing refers to the loss of the energy/power retention capacity of a battery as a function of time and inhibits battery packs from meeting the USABC performance goals.

Most electrolytic compounds are not chemically stable at voltage potentials that exists on the anode, i.e. the negative electrode of a Li-ion battery cell. When a new battery cell is charged for the first time, some of the electrolyte is irreversibly reduced by reacting with free Li-ions near the electrode/electrolyte interphase, forming a thin film of metastable lithium alkyl carbonates, polymers and gaseous products on the surface of the carbonaceous anode. This film is pervious to lithium cations but impervious to electrons and any other chemical species floating in the electrolyte. Electrolytic reduction therefore continues until a steady state is reached where a surface film thick enough to block all the electrons from entry, covers the entire anode surface. It is commonly known as SEI film and prevents the electrolyte from corroding the charged anode due to chemical reduction with little effect on the Li-ion transportation rate through it [42,43].

It has been reported that at elevated temperatures, impervious SEI film starts to break down and dissolve, leaving the anode surface exposed to electrolytic corrosion accompanied with the irreversible loss of lithium. SEI film dissolution also disturbs the physical equilibrium of the metastable organic components of SEI and initiates their transformation into a more stable inorganic form like lithium carbonate. The ionic conductivity or permeability of the SEI film gradually decreases as the percentage of inorganic carbonates in it starts to increase, marking a significant reduction in the energy capacity and power output of the battery cell [6,44]. Fig. 1 identifies the resulting effects of operating a