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Review article

A review of thermal performance improving methods of lithium ion battery: Electrode modification and thermal management system

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HIGHLIGHTS

- The heat generation and dissipation of Li-ion battery are analyzed.
- The hazardous effects of an above normal operating temperature are examined.
- The techniques in electrode modification and battery thermal management are reviewed.
- Various battery parameters and optimization methods are discussed.
- Future research endeavors in battery thermal management systems are provided.

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ABSTRACT

Lithium ion (Li-ion) battery has emerged as an important power source for portable devices and electric vehicles due to its superiority over other energy storage technologies. A mild temperature variation as well as a proper operating temperature range are essential for a Li-ion battery to perform soundly and have a long service life. In this review paper, the heat generation and dissipation of Li-ion battery are firstly analyzed based on the energy conservation equations, followed by an examination of the hazardous effects of an above normal operating temperature. Then, advanced techniques in respect of electrode modification and systematic battery thermal management are inspected in detail as solutions in terms of reducing internal heat production and accelerating external heat dissipation, respectively. Specifically, variable parameters like electrode thickness and particle size of active material, along with optimization methods such as coating, doping, and adding conductive media are discussed in the electrode modification section, while the current development in air cooling, liquid cooling, heat pipe cooling, and phase change material cooling systems are reviewed in the thermal management part as different ways to improve the thermal performance of Li-ion batteries.

1. Introduction

Lithium ion (Li-ion) batteries have emerged as the most promising energy storage technology in recent years due to their higher energy density, lighter weight, no memory effect, and lower self-discharge rate when compared to other rechargeable battery types [1]. The benefits such as long driving range and fast acceleration capability that Li-ion batteries can provide have made them highly recommended as power sources for electric vehicles (EV), hybrid electric vehicles (HEV), and plug-in hybrid electric vehicles (PHEV). The continual commercialization of EVs such as Tesla Model S, Nissan Leaf, BMW i3, and etc., has further promoted a rapid development of Li-ion battery technology and raised a wide public expectation of its future.

Currently, most research into Li-ion batteries focus on the material aspect to improve the specific energy, power, and cycle life, with relatively less attention paid to thermal related issues [2]. However, the operating temperature of Li-ion batteries is closely related to their performance, lifespan, and safety [3,4]. A study from Ramadass et al. [5] has shown that a high operating temperature (from 25 °C to 60 °C) could significantly accelerate the capacity fading of Li-ion cells. Furthermore, overheating can give rise to the occurrence of thermal runaway when the heat in a battery pack is not dissipated properly.

In order to enhance the thermal performance of Li-ion batteries, reducing the amount of heat generated from battery and boosting

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the heat dissipation rate are two feasible options:

1) From the inside, it is the electrode in a battery cell that generates most of the heat during charging/discharging processes, thus, an optimal design of electrode is crucial for minimizing the heat generation in battery. For instance, the decrease of electrode thickness can shorten the distance that electrons and ions travel, leading to lower internal resistance and less heat production. Such modification can fundamentally reduce the heat generation by increasing the electrical and ionic conductivities, and most relevant works are regarding to the advancements in material and processing technologies.
2) From the outside, thermal management system (TMS) implemented in battery packs can help to relieve the rapid temperature rise and improve the stability and safety of Li-ion batteries during charge and discharge procedures. TMS is generally used for battery operating under high discharge rate, and especially for large-scale battery pack that requires long cycle life (>10 years) and is pricy to replace. For example, all HEVs, PHEVs, and EVs are necessary to be equipped with TMS due to the expensive battery repair, high cost of vehicles per se, and relatively low automotive replacement rate. In contrast, basically no TMS is applied on Li-ion batteries used in cellphones, which is mainly attributed to the low cost to substitute a battery, low discharge rate of the cell (under 1C), as well as the fast cellphone upgrade rate.

This paper first looks at the thermal behavior of Li-ion battery and the adverse effects that high temperature exerts on battery performance. Then the solutions from electrode aspect are discussed with the main emphasis on electrode thickness, active material particle size, and anode/cathode material optimization. In what follows, a systematic review of TMSs is presented. Conclusions made in the last section will summarize the advanced electrode and TMS technologies and offer some suggestions for further improvement.

2. Thermal behavior of Li-ion battery

2.1. Energy conservation of Li-ion battery

Fig. 1a shows the schematic illustration of an electrochemical cell inside Li-ion battery. During the discharge process, equal numbers of Li-ions and electrons are generated at the interface of anode and electrolyte. The Li-ions transfer through the electrolyte solution and separator to react with the electrons that flow through the electrode, conductive additives, current collector, and the external circuit. With electrochemical cells stacked or coiled together, prismatic (Fig. 1b) or cylindrical (Fig. 1c) Li-ion battery can respectively be obtained.

The energy conservation equation, which guides the determination of temperature change in Li-ion battery, has the general form of:

$$\rho c_p \frac{dT}{dt} = \nabla \cdot (k \nabla T) + q \tag{1}$$

where the term on the left hand side represents the heat stored inside the battery, q is the volumetric heat generated in the battery. The first term on the right is the three dimensional heat conduction term, and it can be 2D in Cartesian or cylindrical coordinate [6,7] when the temperature gradient in one direction is ignored.

2.1.1. Heat dissipation

Typically, for air cooling system, the boundary condition correlated to the heat conduction term in the x direction can be written as (similar for other directions if same boundary condition is applied):

$$-k \frac{\partial T}{\partial x} = h(T - T_{\text{amb}}) + \varepsilon \sigma \left(T^4 - T_{\text{amb}}^4 \right) \tag{2}$$

where the first term on the right indicates the convective heat transfer, followed by the radiation heat transfer term, which is sometimes omitted for low-temperature batteries. Based on different air flow conditions, different methods of calculating the convective coefficient h should be used as described in the references from the air cooling Section 4.1.

When battery is directly contacted with coolant (liquid or solid) without phase change, the heat flux across the boundary of battery and coolant will be same, i.e.:

$$k \frac{\partial T}{\partial x} = k_c \frac{\partial T_c}{\partial x} \tag{3}$$

and the energy conservation equation in the coolant is:

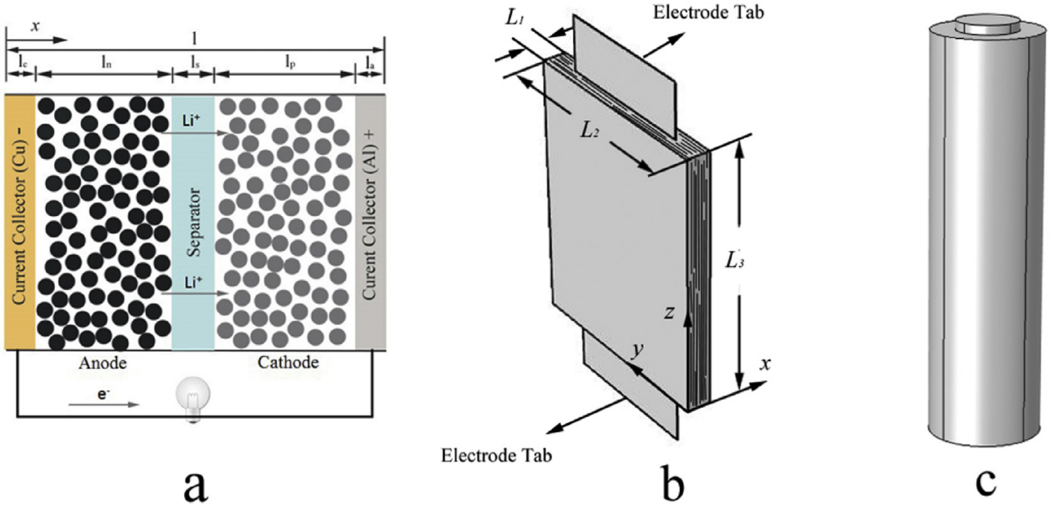

Fig. 1. Schematic illustration of a) an electrochemical cell, b) a prismatic battery, and c) a 18650 cylindrical battery.