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Preventing thermal runaway propagation in lithium ion battery packs using a phase change composite material: An experimental study

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HIGHLIGHTS

- Nail penetration is conducted on Li-ion packs with phase change composite (PCC™).
- Thermal runaway propagation is observed in baseline tests on packs without PCC.
- Propagation is prevented in the corresponding packs with PCC thermal management.
- PCC reduces the max temperature of cells surrounding the penetrated cell by 60 °C.

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ABSTRACT

The safety issues of lithium ion batteries pose ongoing challenges as the market for Li-ion technology continues to grow in personal electronics, electric mobility, and stationary energy storage. The severe risks posed by battery thermal runaway necessitate safeguards at every design level – from materials, to cell construction, to module and pack assembly. One promising approach to pack thermal management is the use of phase change composite materials (PCC™), which offer passive protection at low weight and cost while minimizing system complexity. We present experimental nail penetration studies on a Li-ion pack for small electric vehicles, designed with and without PCC, to investigate the effectiveness of PCC thermal management for preventing propagation when a single cell enters thermal runaway. The results show that when parallel cells short-circuit through the penetrated cell, the packs without PCC propagate fully while those equipped with PCC show no propagation. In cases where no external short circuits occur, packs without PCC sometimes propagate, but not consistently. In all test conditions, the use of PCC lowers the maximum temperature experienced by neighboring cells by 60 °C or more. We also elucidate the propagation sequence and aspects of pack failure based on cell temperature, voltage, and post-mortem data.

1. Introduction

As of May 2016, 1.5 million plug-in electrified vehicles had been sold worldwide [1], and Nissan has announced cumulative sales of over 250,000 fully electric lithium ion powered vehicles as of June 2015 [2]. The electric bike market, which has been growing steadily over the past 5 years, is shifting toward more use of Li-ion [3], and Li-ion batteries are also indispensable to an even wider range of personal electronic devices, such as cell phones and laptops. The high gravimetric and volumetric energy densities of Li-ion cells provide clear advantages over other battery chemistries such as NiMH or lead-acid, but their active materials and electrolytes pose ongoing safety challenges for these applications [4]. Frequent incidents with Li-ion battery fires highlight these safety concerns in personal electronics [5], transportation vehicles [6,7], and even large commercial aircraft [8]. To guard against such accidents, a robust thermal management system is necessary to protect the battery pack under all circumstances, especially when the monitoring or active cooling system fails to detect a cell failure.

These Li-ion fires were caused by thermal runaway, a chemical phenomenon during which the anode, cathode, and electrolyte irreversibly react, generating large amounts of heat that escalate the cell temperature and internal pressure, often with combustion of gases. Several scenarios and factors can trigger thermal runaway [4]. Overheating of the cell can lead directly to thermal runaway by triggering a series of exothermic chemical reactions. Overcharging

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can lead to lithium metal plating on the anode and destabilization of the cathode crystal structure due to excessive delithiation. Mechanical damage, crush, or penetration of a cell can cause a short circuit, leading to rapid heating and thermal runaway. Foreign debris that enters the cell during manufacturing can also cause an internal short circuit, leading to localized heating and subsequent thermal runaway [9,10]. Due to all of these potential hazards, numerous safety mechanisms are often built into Li-ion cells [11]. A safety vent provides pressure relief to prevent electrolyte oxidation and gas generation from reaching dangerous pressures that could burst the cell can. A positive temperature coefficient device (PTC) acts as a current limiter if a cell overheats, preventing high current due to an external short circuit. A current interrupt device (CID) acts like a mechanical switch inside the cell to isolate one of the electrical terminals if internal pressure becomes too high. Porous separators have been designed to shut down all ionic diffusion through the electrolyte if the cell is overheated, mitigating internal short circuits.

The failure of a single cell can generate sufficient heat to trigger the surrounding cells into thermal runaway, leading to propagation, the largest danger of thermal runaway. While the energy release of a single cell event can reasonably be contained, if the liberated heat raises the temperatures of neighboring cells in a pack, it becomes likely that a cascade of propagating cells will result in fire and complete pack destruction [12]. Thus, it is necessary to design pack-level safety features in addition to the cell components. In designing for safety of Li-ion packs, it is helpful to examine the various modes of propagation from one thermal runaway event to other cells. Single cells are known to reach 700 °C in open air during thermal runaway [13,14], giving rise to significant heat transfer via conduction (either through cells in direct contact or through external current collectors), convection, and radiation [15]. Additionally, the venting of vaporized electrolyte and its combustion can contribute an even larger amount of heat [16,17], and the flow of these hot gases and combustion make thermal runaway propagation a largely unpredictable process. Experimental studies have therefore often yielded results with irreproducible details in the temperature, voltage, and propagation behavior [18].

Literature reports of experimental thermal runaway testing of full Li-ion cells are abundant, particularly from calorimetric testing [19–21]. Modeling using cell electrochemical and thermal properties has also been investigated by several groups to predict cell performance in various abuse conditions or to validate experimental results [22–24]. However, data for thermal runaway in a full battery pack is much less common. Lopez et al. [15] conducted several propagation tests in small packs of 18650 and wound prismatic cells. Their temperature data and post-test autopsies demonstrated lower cell temperatures and less likelihood of propagation for larger spacing between cells, or with the use of intumescent or radiative barrier materials between the cells. Feng et al. [25,26] studied the propagation behavior in a battery module of 12 pouch cells using nail penetration. Their experimental temperature and voltage data clearly showed how propagation can occur when one cell is forced into thermal runaway and quickly heats the adjacent cells. Still, a more detailed understanding of cell-to-cell propagation is crucial for guiding safe designs. Specifically, since propagation within a battery pack is strongly influenced by its thermal management system, experimental studies are needed to evaluate the merits of various thermal management options.

Many papers have been published on the importance of a robust thermal management system to operate the battery pack in normal and abuse conditions [12,27,28]. Li-ion batteries most often utilize air, liquid, or passive thermal management [29]. While liquid cooling typically provides the best heat rejection from the battery, these systems require power from the battery to operate and can leak. Forced air cooling avoids leakage concerns but often produces large temperature gradients across the battery pack. Passive thermal management is an attractive alternative because of its lower cost, weight, and complexity compared to liquid or air, but passive systems cannot achieve the same amount of heat rejection. One promising passive thermal management approach is the use of phase change composite materials (PCC™) [28,30–32]. PCC is a composite of wax and graphite that absorbs heat during battery operation or abuse conditions, while maintaining good temperature uniformity across the pack. As a battery heats up – due to regular discharge or a single cell thermal runaway – the energy is absorbed as the wax transitions from solid to liquid phase, preventing the cells from reaching dangerous temperatures. Once the battery is at rest, the stored heat is then rejected to the environment either through natural convection or coupling to a small active cooling system. Compared to other passive systems, PCC exhibits good heat rejection due to its high thermal conductivity (20 W m^{-1} K^{-1}) compared to air (0.024 W m^{-1} K^{-1}) or potting compounds (~2.5 W m^{-1} K^{-1} [33]) typically used in packs of cylindrical cells.

This paper details the first experimental thermal runaway propagation study using a phase change composite material for battery thermal management. The experiments aim to understand the propagation behavior when interstitial PCC is placed between Li-ion cells, compared to a baseline test with air between the cells. Nail penetration is used to trigger a thermal runaway event in one cell of the pack, and the response of the neighboring cells is recorded. The collected temperature, voltage, and post-mortem analyses shed light on the importance of parallel cells' short circuit behavior during thermal runaway events, demonstrating that it is a source of significant heat generation in the pack during a single cell thermal runaway. The PCC is shown to prevent cell-to-cell propagation when parallel cell short circuiting occurs, while the corresponding tests without PCC show full propagation.

2. Experimental

2.1. Pack construction

To illustrate the effect of using PCC on pack thermal runaway, we chose an electric bike battery because its general characteristics are representative of most small electric mobility packs and some modules used for larger stationary energy storage. Although every pack design will exhibit a unique response to thermal abuse, the general observations and lessons learned from this pack should provide a guide for how PCC influences thermal runaway. The pack design used 18650 form factor cells in a configuration of 10 strings in series, each containing 4 cells in parallel (10s4p). The pack specifications are summarized in Table 1. The cell used in this study was a high-energy cell (2.85Ah) supplied by a top tier, globally recognized cell manufacturer. Cell specifications are provided in Table 2.

The construction process was the same for all packs tested,

Table 1
Pack specifications.

Specification	Value
Configuration	10s4p
Energy (Wh)	413
Voltage, nominal (V)	36.2
Mass (kg)	2.75
Specific energy (Wh kg^{-1})	150
Dimensions (cm)	32 × 9 × 13
Casing	Aluminum & plastic