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Study of the fire behavior of high-energy lithium-ion batteries with full-scale burning test

Ping Ping [a, b], QingSong Wang [a, c, *], PeiFeng Huang [a], Ke Li [a], JinHua Sun [a, *], DePeng Kong [d], ChunHua Chen [e]

[a] State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei 230026, PR China
[b] College of Chemical Engineering, University of Petroleum of China, Qingdao 266580, PR China
[c] Collaborative Innovation Center for Urban Public Safety, Anhui Province, Hefei 230026, PR China
[d] College of Mechanical and Electronic Engineering, University of Petroleum of China, Qingdao 266580, PR China
[e] Department of Materials Science & Engineering, University of Science and Technology of China, Hefei 230026, PR China

HIGHLIGHTS

- First investigation of the fire behavior of 50 Ah $LiFePO_4$/graphite batteries.
- The combustion of the battery takes the form of multiple jets of flame.
- The inner short circuit is the ultimate initiator of the fire.
- The maximum temperature, heat release rate and heat of combustion determined.
- Heat release rate, heat generation and mass loss are related to the state of charge.

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ABSTRACT

A full-scale burning test is conducted to evaluate the safety of large-size and high-energy 50 Ah lithium–iron phosphate/graphite battery pack, which is composed of five 10 Ah single cells. The complex fire hazards associated with the combustion process of the battery are presented. The battery combustion behavior can be summarized into the following stages: battery expansion, jet flame, stable combustion, a second cycle of a jet flame followed by stable combustion, a third cycle of a jet flame followed by stable combustion, abatement and extinguishment. The multiple jets of flame indicate serious consequences for the battery and pose a challenge for battery safety. The battery ignites when the battery temperature reaches approximately 175–180 °C. This critical temperature is related to an internal short circuit of the battery, which results from the melting of the separator. The maximum temperature of the flame can reach 1500 °C. The heat release rate (HRR) varies based on the oxygen generated by the battery and the Joule effect of the internal short circuit. The HRR and heat of combustion can reach 49.4 kW and 18,195.1 kJ, respectively. The state of charge of the battery has a significant effect on the maximum HRR, the overall heat generation and the mass loss of the battery.

1. Introduction

Lithium-ion batteries are widely used as power sources for electrified portable devices and are currently under consideration for use in electric vehicles (EVs) and power plants [1]. However, recurrent fire incidents involving cell phones, laptops, EVs and airplanes have raised increasing concern regarding the safety of lithium-ion battery applications [2,3]. Because of its unique chemical composition and electrical-energy-storage properties, a lithium-ion battery may rupture, ignite or even explode when it is subjected to abuse such as overheating, overcharging, a short circuit, a puncture or compression [2,4]. Numerous research studies has been conducted in an effort to enhance the thermal stability of the battery materials [5–7], decrease the flammability of battery compositions [4,8] and improve the thermal management of battery modules [9]. Benefitting from these efforts, high-quality

* Corresponding authors. State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei 230026, PR China.
E-mail addresses: pinew@ustc.edu.cn (Q. Wang), sunjh@ustc.edu.cn (J. Sun).

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lithium-ion batteries have been designed that suffer less than one reported incident for each million batteries produced [10]. However, for EVs and power plants, hundreds or even thousands of lithium-ion batteries will be required, either as power sources or for energy storage. With such an increase in the number of batteries in use, the failure rate will also increase proportionally, which remains a major barrier to the application of large-scale and high-energy lithium-ion batteries.

To gain an understanding of the mechanism involved in the thermal stability deterioration of batteries, many studies have focused on the reactions that occur inside a battery up to the point of thermal runaway [11–13]. However, few publically available data regarding large-scale lithium ion batteries are available. Small-scale combustion tests of 2.9 Ah $LiMn_2O_4$/graphite batteries have been performed by the French National Institute for Industrial Environment and Risks (INERIS) [14], in which the thermal and toxic threat of battery fires was quantified based on the Fire Propagation Apparatus. FM Global has conducted large-scale burning tests of thousands of 18,650 cells (2.6 Ah, $LiCoO_2$ based) to evaluate the flammability of small-size lithium-ion batteries in a rack storage array and the effectiveness of a protection system [15]. However, all the tests mentioned above have concerned only small-format cells or battery packs consisting of small cells. Large-size batteries have been investigated only rarely in published studies.

In this paper, we present full-scale burning tests of 50 Ah $LiFePO_4$ battery packs based on the ISO 9705 Full-Scale Room Fire test apparatus. The battery pack is composed of five 10 Ah single cells. The full-scale room test is especially suitable for products that for some reason cannot be tested on a small laboratory scale, for example, thermoplastic materials, materials with insulating substrates, joints, and surfaces with high irregularity [16]. Using this apparatus, the burning phenomenon, mass loss, heat release rate (HRR) and temperature variation of burning batteries with various states of charge (SOC) are analyzed. The HRR calculated by measuring the oxygen consumption is modified to account for the electrochemical properties of lithium-ion batteries. The critical temperature and the direct trigger of the ignition of the battery are determined. The fire hazards that arise when large-size, high-energy lithium-ion batteries are involved in a fire scenario are presented.

2. Experimental

2.1. Thermal analysis of a coin cell

To decipher the sequence of events leading to thermal runaway in the $LiFePO_4$/graphite system, a thermal analysis of a CR2032 coin cell with the same chemistry as the 50 Ah battery pack was performed. The capacity of CR2032 coin cell is 8.12 mAh. The total mass of the positive disk, negative disk, electrolyte and separator in the CR2032 coin cell is 0.156 g. After normal assembly and pre-cycling to 100% SOC as in Ref. [7], the cells were placed in a glove box and disassembled. All substances in the open cell were transferred into a high-pressure stainless steel vessel for thermal analysis using a C80 microcalorimeter, which is an effective apparatus for the thermal analysis of battery materials [7]. The heating rate in the C80 test was set to 0.2 °C min^{-1}, and the materials were heated from 30 °C to 300 °C.

2.2. Apparatus and method

Fig. 1 presents a schematic diagram of the full-scale burning test apparatus. The apparatus was designed based on the ISO 9705 Full-Scale Room Fire Test for Surface Products [16]. In the standard ISO 9705 test system, propane fuel is used as the ignition source. In this study, a 3 kW radiation heater without any other ignition source was employed to avoid any interference from propane combustion in the test results. The heater was placed at the same height as the battery, at a horizontal distance of 100 mm. To decrease the propagation distance of the combustion smoke, the battery was placed immediately below the exhaust hood rather than in the room or the corner.

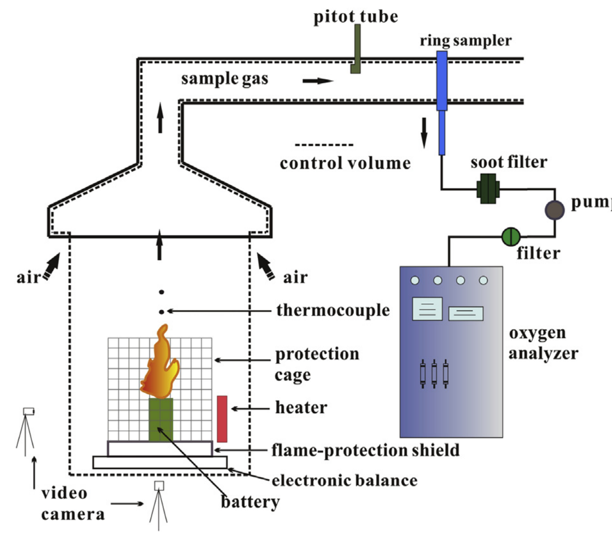

Fig. 1. Schematic diagram of the full-scale burning test apparatus.

To prevent the test system from being damaged by a battery explosion or other runaway fire scenarios, the battery was placed on a flame-protection shield in a stainless steel protection cage. An electronic balance was placed below the protection shield to simultaneously measure the mass loss of the battery. Two video cameras, protected by fireproofing boards, were mounted outside the exhaust hood to monitor the combustion behavior and the shape of the flame.

The combustion products were captured in their entirety and mixed with ambient air. The flow rate and temperature of the product–air mixture were measured by a Pitot tube and a thermocouple, respectively. Sample gas was first obtained from the ring sampler and then filtrated and dewatered. Finally, the sample gas was tested using a Gas Analysis Instrumentation Console (Fire Testing Technology Ltd, FTT) to obtain the online quantifications of O_2, CO and CO_2, which constitute the basic information necessary to determine the HRR.

Figs. 2 and 3 present schematic diagrams of the thermocouple setup. To evaluate the heat threat and fire hazard, 25 K-type (chromel–alumel) thermocouples were employed to measure the temperature of the battery fire. Of these, 7 thermocouples were located on the surface of battery, and the remaining thermocouples were placed above the surface of the battery.

To confirm the test results, each test was repeated twice. However, the first of each of these repeated tests was treated as a preliminary test to ascertain the potential of battery explosion, the location of the jet orifice and the flame shape. Using this information, the most effective placement of the thermocouples could be determined. However, some real-time data were not recorded during the preliminary test.

2.3. Battery details

Apart from the CR2032 coin cell, the primary subjects of this study were commercial 50 Ah $LiFePO_4$/graphite battery packs. This