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An experimental study on burning behaviors of 18650 lithium ion batteries using a cone calorimeter

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HIGHLIGHTS

- Fire risks and behaviors of charged lithium ion batteries were investigated.
- The thermal runaway of charged lithium ion batteries was experimentally studied.
- The effects of state of charge on burning behaviors of LIBs were evaluated.
- The heat release rates of LIBs were experimentally measured.
- The internal generated oxygen accounts for up to 13% of total heat release rate.

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ABSTRACT

Numerous of lithium ion battery fires and explosions enhance the need of precise risk assessments on batteries. In the current study, 18650 lithium ion batteries at different states of charge are tested using a cone calorimeter to study the burning behaviors under an incident heat flux of 50 kW m^{-2}. Several parameters are measured, including mass loss rate, time to ignition, time to explosion, heat release rate (HRR), the surface temperature and concentration of toxic gases. Although small quantities of oxygen are released from the lithium ion battery during burning, it is estimated that the energy, consuming oxygen released from the lithium ion battery, accounts for less than 13% of total energy released by a fully charged lithium ion battery. The experimental results show that the peak HRR and concentration of toxic gases rise with the increasing the states of charge, whereas the time to ignition and time to explosion decrease. The test results of the fully charged lithium ion batteries at three different incident heat fluxes show that the peak HRR increases from 6.2 to 9.1 kW and the maximum surface temperature increases from 662 to 934 °C as the incident heat flux increases from 30 to 60 kW m^{-2}.

1. Introduction

The lithium ion batteries (LIBs) have been widely used in electronic products, vehicles and aerospace applications owing to their excellent features of high power capacity, stable voltage, long life cycle and low self-discharge [1,2]. However, the LIBs fires and explosions have occurred occasionally in the transportation because their thermal stability is sensitive to temperature, overcharging, extrusion and collision. For instance, the Asiana Airlines' B747 freighter crashed into the sea on July 29, 2011, killing two pilots, due to a cargo fire caused by LIBs [3]. Therefore, to ensure the safety transportation of LIBs, it is worthwhile to study the burning behaviors of LIBs.

Previous researches have reported that the LIBs underwent thermal runaway reactions which lead to the combustion of organics electrolyte and rupture under heating conditions [4,5]. Jhu et al. [6] conducted a set of experiments in an adiabatic calorimeter and found that the charged LIBs were more hazardous than uncharged ones and the maximum surface temperature of the charged LIB could reach 903 °C. Roth et al. [7] showed that the thermal runaway reactions of LIBs were affected by the state of charge (SOC) using an accelerating rate calorimeter. Increasing SOC reduced the onset temperature of thermal runaway reactions and increased acceleration rate. Ribière et al. [8] demonstrated the fire-induced hazards of Li-ion polymer batteries using a Tewarson calorimeter. It was found that the HRR and toxic gases productions depended significantly on the SOC. Golubkov et al. [9] concluded that the maximum surface temperature of LIBs with the format 18650 was 850 °C as measured using a custom-designed test stand. The above researches have concentrated on the LIB burning

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behaviors while heated using different calorimeters. However, cone calorimeter, as an important apparatus in hazardous material assessments, has not yet been applied to evaluate the burning behaviors of LIBs. Of the many fire reaction properties measured by the cone calorimeter, it is generally recognized that the HRR is the most important factor in controlling fire hazards, which corresponds directly to the intensity of fire. The HRR has been studied by Ribière using the Tewarson calorimeter. Their estimate of the maximum energy, liberated by the Joule effect which cannot indeed be related to O_2 consumption, is about 10% of the overall energy of a fully charged Li-ion polymer battery. The present work is to estimate the HRR of format 18650 LIB using the cone calorimeter. The HRR is estimated by oxygen depletion and mass loss methodologies, providing experimental data to infer the amount of released energy using up oxygen liberated from the LIB. Then this work investigates the burning behaviors of LIBs. The experiments focus on two aspects: (1) the effect of the SOC on the burning behaviors of LIBs, (2) the burning behaviors of the fully charged LIBs at different incident heat fluxes. The collected data by the cone calorimeter can be either used directly by researchers or used as input data for mathematical models to analyze the thermal and chemical threats [10].

2. Brief introduction to format 18650 lithium ion battery

An 18650 lithium ion battery mainly consists of a positive electrode (cathode), a negative electrode (anode), a separator and electrolyte. The cathode is a lithium cobalt oxide and the anode is graphite. Lithium ions are extracted from the anode and flow into the cathode during discharge. The ions reverse direction during charge [11].

As shown in Fig. 1, the LIB has a diameter of 18 mm and a length of 65 mm. The separator is a very thin sheet of micro-perforated plastic allowing ions to pass through, which is located between the cathode and anode separating the positive and negative electrodes. The electrolyte is a solution consisting of organic solvent and inorganic salt, which provides the media for lithium ions transport. The LIB is constructed by winding long strips of electrodes into a "jelly roll" configuration. Electrode stacks or rolls can be inserted into hard cases that are sealed with gaskets. The enclosure of a hard case cell is aluminum. A burst disk is used as safety vent [12].

3. Experimental setup

3.1. Samples

The LIBs used in the current study are manufactured by Sanyo. Table 1 shows the information of LIBs. The nominal capacity of the LIB is 2.6 Ah. The LIB is charged to the expected SOC and then put in the cone calorimeter to research the burning behaviors.

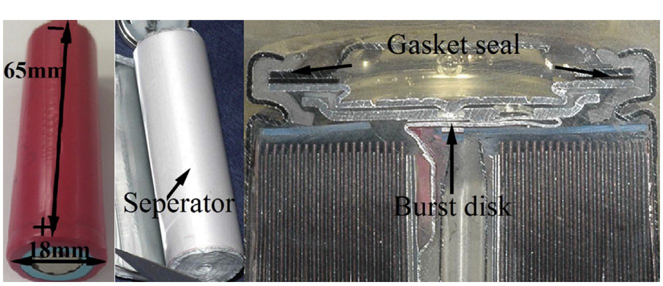

Fig. 1. Structure of the lithium ion battery.

Table 1
Information of commercial 18650 lithium-ion batteries.

Sample	Producer	Type	Capacity (Ah)	SOC (%)
A	Sanyo	UR18650FM	2.6	100
B	Sanyo	UR18650FM	2.6	70
C	Sanyo	UR18650FM	2.6	65
D	Sanyo	UR18650FM	2.6	50
E	Sanyo	UR18650FM	2.6	0

3.2. Apparatus

The cone calorimeter experiments were carried out according to the procedures in the ISO 5660-1 standard [13]. The samples were put horizontally in a sample holder staying on a load cell. Ceramic fiber blanket was used underneath the samples for thermal insulation. The sample holder was covered by a wire grid to prevent the LIB explosion splashing sparks from attaching the cone heater during the test. Two K-type thermocouples were wound around the sample using steel wires, which attaching the sample surface at different locations in order to obtain the surface temperature. The cone calorimeter was calibrated according to the procedure in the ISO 5660-1 standard before experiments. Protection screen was put down to prevent explosion splashing sparks from widely spreading. Fig. 2 presents the experimental setup in the cone calorimeter. As shown in Fig. 2, the surface of the sample was radiated by the cone heater and heated up. The combustion productions were collected by an exhaust hood and transported away through a ventilation system. CO and CO_2 gas analyzers were used to measure the generation of carbon monoxide and carbon dioxide. An O_2 analyzer was used to measure the oxygen depletion. The fan flow rate was set as 24 L s^{-1}. A camera was positioned to observe the burning process of the LIB. The ambient temperature was around 30 °C with natural ventilation. The experiments ended when flame was extinguished. Each experiment was repeated at least three times and the average values were taken.

During the test, the following parameters were determined: mass loss rate, the time to ignition and the time to explosion, the yields of CO and CO_2, the surface temperature and HRR. The sample was weighted using a load cell. The time to ignition is defined as the duration time which is needed by the sample from being exposed to incident radiation till a visible and sustainable flame is firstly established. The time to explosion is time from experiment start to explosion. The observation of time to ignition and explosion were recorded. The temperature readings were recorded using the Agilent 34970A data acquisition system. The HRR and the yields of CO and CO_2 were recorded automatically by the cone calorimeter.

4. Results and discussion

4.1. Burning process

The experimental process shows the LIB reacts strongly while being heated. Fig. 3 presents the typical burning process of a fully

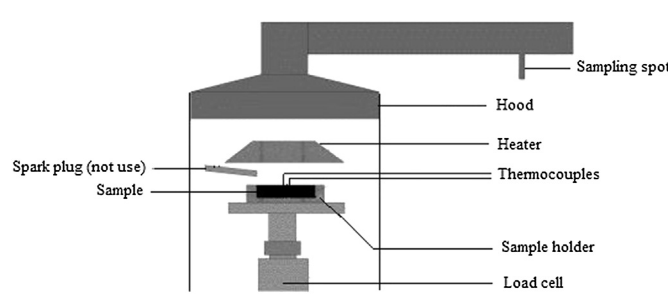

Fig. 2. Experimental setup in the cone calorimeter.