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Ignition and combustion characteristics of lithium ion batteries under low atmospheric pressure

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A B S T R A C T

Numerous of lithium ion battery fires or explosions enhance the need of fire control technology. To investigate the effectiveness of depressurization on the fire suppression of lithium ion batteries in an aircraft environment, an experimental and theoretical study is taken on the ignition and combustion characteristics of lithium ion batteries under an incident heat flux of 50 kW/m^2 using a low pressure tank. Several fire parameters are measured and analyzed, including time to deflation, ignition and thermal runaway, surface and flame temperatures as well as average mass loss rate. Experimental results show the average mass loss rate and surface and the peak flame temperatures decrease whereas the time to deflation, ignition and thermal runaway increase with the reduction of the pressure, demonstrating a lower fire risk. The 30 kPa is the critical pressure for the ignition of lithium ion battery under 50 kW/m^2 radiation heat flux. However, the pressure shows limited influence on the ignition temperature, radiation coefficient and time interval between the time to ignition and thermal runaway. The effect mechanisms of pressure on fire parameters are revealed. An empirical model is developed to predict the average mass loss rate of lithium ion battery under low atmospheric pressure.

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1. Introduction

Lithium-ion batteries (LIBs) have to be shipped by aircraft under current tremendous demands. Following the United States Code of Federal Regulations (CFR Title 49), the LIBs are classified as Class 9 hazardous material [1], showing the risks of flammability or explosion. Due to the lack of the corresponding fire control technology, the LIBs fires or explosions could occur in air transportation, resulting in catastrophic deaths and properties loss. For example, in September 2010, United Parcel Service' B747 freighter crashed in Dubai and killed two pilots [2]. During the flight, the pilot tried to suppress the LIBs fires by depressurizing the main cabin but finally failed. Thus, the related fire hazards and fire control technology of the LIBs have been greatly concerned by researchers and engineers.

Currently, United States Federal Aviation Administration (FAA) accepts the procedure to control in-flight cargo fires in freighter by turning off the ventilation and then depressurizing the cargo hold [3]. Those LIBs transported by air must also pass the altitude simulation test, which qualifies a LIB under low atmospheric pressure such as those may be experienced on onboard aircraft. This test requires the LIB to be stored at a pressure of no more than 11.6 kPa for at least 6 h, without showing vent or ignition. Besides, the interior pressure of an aircraft during the flight is usually lower than sea level atmospheric pressure. Generally, most of the freighters are not pressurized and the internal pressure can reach about 26 kPa during the cruise phase while aircraft cabin air is pressurized to 75–84 kPa following FAA regulations [4] to enable passengers' comfort and minimize the fuselage structure fatigue. As it is inevitable to put the LIBs under low atmospheric pressure in the air transportation, understanding their ignition and combustion characteristics under low atmospheric pressure is then of great importance to help suppressing the related fires.

Previous efforts have been largely focusing on the combustion characteristics of other solid fuels under low atmospheric pressure [5–9]. For example, Wieser et al. [5] conducted small-scale fire tests of smoldering wood, glowing cellulose and polyurethane foam at low atmospheric pressure locations with altitudes from 400 to 3000 m. The experimental results demonstrated that the mass loss rate (*MLR*) was proportional to one-third power of atmospheric pressure. Li et al. [6] and Wang et al. [7] obtained from experiments that the *MLR* of wood fire in Lhasa (64 kPa) was greater than that in

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Hefei (100 kPa). Cardboard box fires specified by FAA Minimum Performance Standard [8] were studied in both Hefei and Lhasa by Niu et al. [9]. It was obtained that the *MLR* decreases while plume temperature increases under lower pressure.

The influences of pressure on the ignition characteristics have also been addressed for some solid fuels [10–13]. Dai et al. [10] carried out spontaneous ignition experiments of pine wood in Lhasa, showing a reduction in time to ignition (*TTI*) when comparing to those similar cases at the standard atmospheric pressure. Kishore et al. [11] examined the effect of pressure on the spontaneous ignition of polymer, obtaining decreased *TTI* under reduced pressure. McAllister et al. [12,13] investigated piloted ignition characteristics of polymer and obtained the same results as well.

The above studies have confirmed that the pressure shows important effects on the flammability of those solid combustibles. Although many studies have been taken regarding LIBs fires under standard atmospheric pressure [14–18], very few studies have been focusing on the LIBs fires under low atmospheric pressure. Those rare existing studies on primary lithium batteries fires in both Hefei and Lhasa [19] were taken, which limits the tested range and continuity within the range. To address the influencing mechanisms of pressure on the LIBs fires, it is significant to test the LIBs fires in a relatively big range with continuously dropped interval.

Therefore, the influences of pressure on the ignition and combustion characteristics of the LIBs were systematically investigated and discussed in a relatively big range of 30–101 kPa atmospheric pressures with an interval of 10 kPa. The *TTI*, surface and flame temperatures, and *MLR* are measured and analyzed. Based on the experimental results, the possible relationships between the combustion characteristics of the LIBs (e.g. flame temperature and *MLR*) and pressure will be revealed. The related research outcomes are useful to provide guide for the development and improvement of related standards for the LIBs in the air transportation.

2. Experimental methodology

2.1. Apparatus

The experimental equipment consists of a low atmospheric pressure tank, pressure controlling system and other auxiliary systems, as shown in Fig. 1. The internal dimension of the low atmospheric pressure tank is 1.0 m (long) × 1.0 m (wide) × 0.6 m (high). A door with fire resistant glass window in the middle is located in one side of the low atmospheric pressure tank, while the glass window is used for observation. Inside the low atmospheric pressure tank, a horizontal rail is installed at the ceiling. A radiation panel (0.3 m × 0.3 m) is mounted on the horizontal rail, which can be used to adjust the position of radiation panel. The radiation source is realized by an infrared panel heater which can provide a uniform and up to an incident heat flux of 100 kW/m^2 radiation heat on sample surface. A stainless steel sample holder is set under the radiation panel and its underneath is an electronic balance with a resolution of 0.1 g to record the mass loss of sample during the experiment. An insulator is put on between the sample holder and electronic balance in order to prevent the damage caused by high temperature.

During the experiment, sample was put vertically in the sample holder and fixed by a screw. The vertical distance between the radiation source and sample surface was fixed at 16 cm. A shutter was used during the increasing period of the radiation heat to prevent sample heated. When the radiation source reached the target level, the shutter was removed and sample can immediately receive the designed radiation heat. No spark plug was used and the experiment can be considered as spontaneous ignition. Two K-type thermocouples with 1 mm diameter were wound around the sample using steel wires, which attached the center of sample side surface in order to obtain the surface temperature during the test. The gas-phase temperatures between radiation source and sample surface were measured by four K-type thermocouples, which were positioned along the center of sample and 1–16 cm above the surface with an interval of 5 cm. The measured temperatures were recorded based on an Agilent 34970A data acquisition system. The temperature data used in this study were the direct reading from the two thermocouples with an uncertainty of less than 10%. A digital camera was placed in front of the window to record the burning processes.

The pressure controlling system is made up of a vacuum pump, a central control unit and a stabilization tank. A duct is used to connect the low atmospheric pressure tank with a vacuum pump through one side-wall, while an air inlet with an electromagnetic valve is utilized to control the inside pressure automatically. A touch screen installed at the central control unit is used to manage the experimental processes.

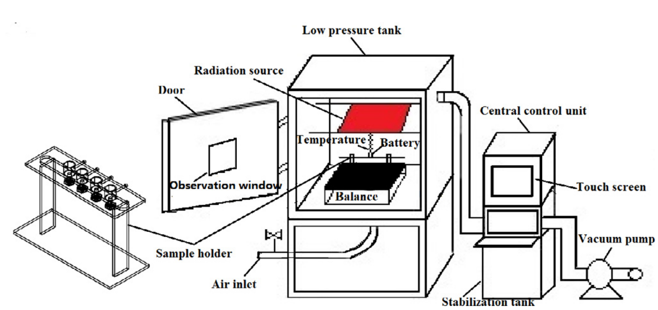

Fig. 1. Schematic of the experimental setup in this study.

2.2. Samples

Popularly transported 18650-type LIBs were adopted in the current study, which were manufactured by Scud Electronic (Shenzhen, China) Co. Ltd. The capacity of the LIB is about 2.6 Ah. As shown in Fig. 2, the LIB has a diameter of 18 mm and a height of 65 mm. The LIB mainly consists of a cathode, an 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. Those ions reverse direction during

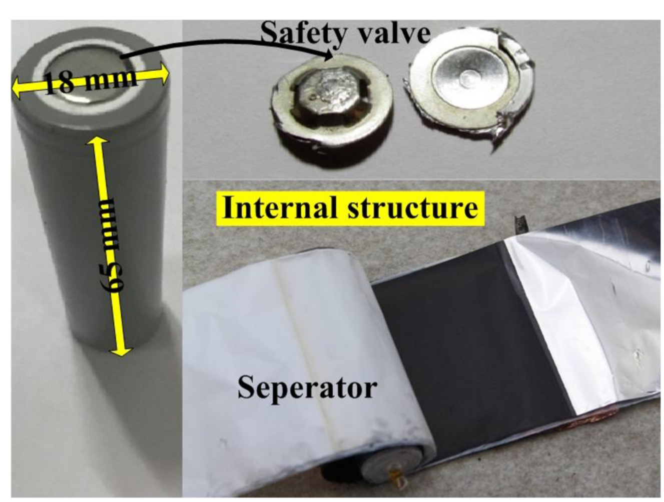

Fig. 2. Structure of the tested LIB.

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