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Experimental Study on Suppression of Lithium Iron Phosphate Battery Fires

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Abstract
Lithium-ion battery applications are increasing for battery-powered vehicles because of their high energy density and expected long cycle life. With the development of battery-powered vehicles, fire and explosion hazards associated with lithium-ion batteries are a safety issue that needs to be addressed. Lithium-ion batteries can go through a thermal runaway under different abuse conditions including thermal abuse, mechanical abuse, and electrical abuse, leading to a fire or explosion. The NIOSH Mining program is conducting research to prevent and respond to lithium-ion battery fires for battery electric vehicles in the mining industry. In this study, experiments were conducted to investigate the effectiveness of different suppression systems including dry chemical, class D powder, and water mist for lithium iron phosphate battery pack fires. The effects of activation time and release time of the water mist system on the suppression of lithium-ion battery fires were studied. The results of this study may be helpful for developing strategic firefighting and response plans for battery-powered vehicles used in mining.

Keywords Lithium-ion battery · Thermal runaway · Fire suppression · Experiments

1 Introduction

Lithium-ion (Li-ion) batteries are finding more use as power sources in the mining industry because of their high-power output combined with their small size and weight. Battery electric vehicles are seen as desirable alternatives to the use of diesel-powered equipment because of concerns over the adverse health impacts from worker exposures to diesel particulate matter. However, Li-ion batteries are known to pose significant fire and explosion hazards when they are compromised as a result of physical damage or extreme operating conditions such as high temperature, overcharging, over discharging, and external/internal short circuit as reviewed by Kong et al. [1], Wang et al. [2], and Sun et al. [3]. When a lithium-ion battery is exposed to excessive operating conditions, its internal temperature may exceed a normal operating range allowing the active component materials to decompose or react with each other, eventually leading to thermal runaway. In theory, thermal runaway occurs when heat losses to the environment are less than the heat generated by exothermic reactions inside the battery. The accumulated heat drives the temperature increase which produces an exponential increase in the reaction rates. During thermal runaway, potentially large quantities of gases can be emitted. These gases are usually high-temperature, combustible, and toxic [4–9]. For a battery pack consisting of hundreds of cells, the fire hazard can be much greater when many cells are undergoing thermal runaway in a short time. Potential fire or explosion intensities involving these batteries may pose significantly greater hazards due to the sizes needed to power large mine equipment [10]. Several battery fire incidents have occurred in underground mines in the early stages of battery electric vehicle deployment [11]. Any Li-ion battery fire or explosion can pose a significant threat to personnel safety and cause property damage. To reduce the hazard of Li-ion battery fires, it is critical to suppress the battery fire effectively and timely.

There are four basic approaches to suppress a typical fire: cooling, isolation, smothering, and chemical suppression. There is no specific order in approaching to suppress a typical fire. A fire can be extinguished by one approach or multiple approaches at the same time. A typical fire cannot

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occur without the presence of oxygen. However, a lithium-ion battery fire is not a typical fire as the battery contains certain oxidizing agents and some reactions do not need oxygen from the air, making suppression of a battery fire much more challenging. Even after a battery fire is extinguished, reignition can occur as the reactions inside the battery pack may persist. The National Transportation Safety Board (NTSB) investigated three electric vehicle battery fires and found that the vehicles' Li-ion batteries reignited 15 times in total [12]. Laboratory-scale experiments have been conducted to study the suppression of Li-ion battery cell or cell array fires using different suppressants including water mist, dry chemical, carbon dioxide, foam, and clean agent that is electrically non-conductive, volatile, or gaseous, and that does not leave a residue upon evaporation [13–15], and the results indicate that water mist/spray has a better suppression effect than other suppression agents that were able to extinguish the open flames of the Li-ion battery, but the re-ignition could not be avoided. Therefore, water has been gaining more attention recently for suppressing Li-ion battery fires and mitigating thermal runaway propagation in battery packages [16–20]. However, those battery suppression experiments mainly focused on one cell or a few cells, and results may not be directly applied to large battery packs. There is limited experimental data available on the effective suppression of Li-ion battery pack fires using different suppression agents. For a battery pack consisting of hundreds of cells, the fire hazard can be much greater when many cells are undergoing thermal runaway in a short time. Potential fire intensities involving these batteries may pose significantly greater hazards due to the sizes needed to power large equipment [10]. These potential fire hazards need to be assessed, and techniques developed to prevent and suppress large battery pack fires.

For battery electric vehicles used in underground mines, water may not be readily available, or the amount of water may be limited. There is also a research gap on how to suppress battery fires effectively and protect mine workers in underground mines where there is a limited supply of water. In this study, suppression experiments were conducted for lithium iron phosphate (LFP) battery pack fires using water, dry chemical, and class D extinguishing powder. Water is readily available and used most often for fire suppression. Dry chemical is widely used for equipment fire suppression in the US mining industry. Class D powder is suitable for suppressing combustible metal fires such as lithium metal battery fires. However, Li-ion battery fires are not a combustible metal fire. Class D powder suppression agent is selected to demonstrate that although it is effective in extinguishing a metal fire, it is not effective in suppressing a Li-ion battery fire. Other fire suppression systems, such as carbon dioxide and clean agents, are not evaluated in this study as they are not commonly used in the mining industry. To utilize water most effectively for battery fire suppression, the effects of activation time, release time, and flow rate on suppression of lithium-ion battery fires were investigated. The experimental results from this study may be used to determine appropriate fire suppression agents and systems and develop effective firefighting strategies for lithium-ion battery fires in underground mines.

2 Experimental Setup

Li-ion battery fire suppression experiments were conducted in a container with dimensions of 12-m long, 2.4-m wide, and 2.85-m high with a data acquisition and test observation trailer nearby. A fan is installed at one end of the container, and the other end is open as shown in Fig. 1. The facility is equipped with different fire suppression systems including dry chemical, water spray/mist, and class D powder. The fire suppressant release nozzle is directed downward and

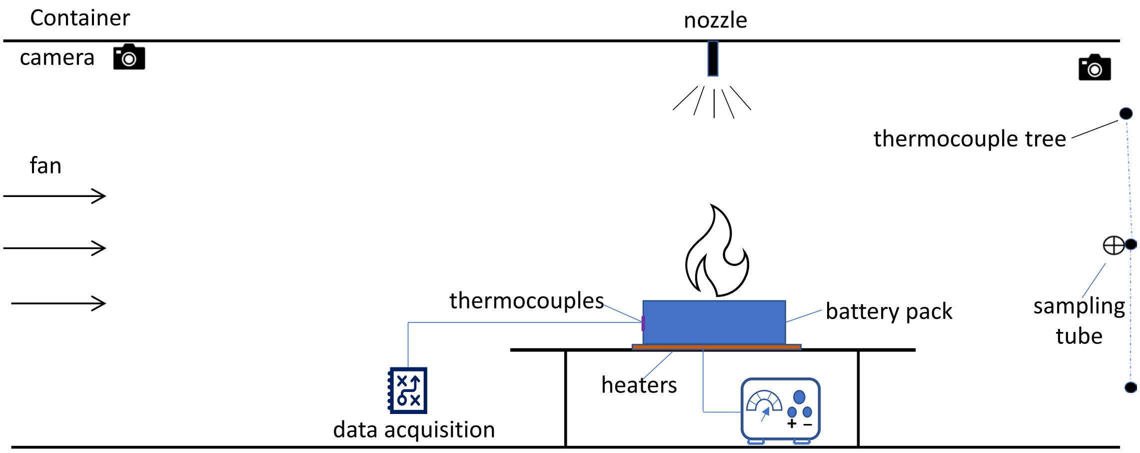


Fig. 1 Schematic of battery fire suppression test setup

placed above the battery. The suppression system can be manually activated from outside the container. Activation time is when the suppressant is first deployed, and release time is the duration of release of the suppressant. At the exit of the container, thermocouple trees and gas sampling tubes are installed to measure temperature and collect samples of exiting gases. The ventilation velocity measured at the exit was set at 0.2 m/s for the tests. Two cameras are installed inside the container for test monitoring.

The Li-ion battery used for the tests is a 12-V 35Ah lithium iron phosphate (LFP) battery pack consisting of 24 cylindrical cells. LFP batteries are widely used in battery electric vehicles and energy storage systems. The LFP battery is one of the Li-ion battery chemistries commonly used in the mining industry to power mine vehicles [21]. The thermal runaway and fire behavior of LFP batteries have been previously studied [22–24]. Before each test, the battery pack was charged to the 100% state. During the tests, the battery pack was placed on two 750-W heater strips to induce thermal runaway. Eighteen K-type thermocouples were attached to the outer cell surfaces of the battery pack to measure the battery temperature as shown in Fig. 2. For each test, when one battery cell reached thermal runaway, the heaters were turned off and the fire suppression system was activated between 0 and 60 s after a stable flame was established. The suppressants were applied to exposed cells rather than the battery enclosure surface as the top casing was removed. An attempt was made initially to mimic actual installation fixtures of battery packs without opening the battery casing that is combustible. It was found that the burning of the battery casing complicated the Li-ion battery thermal runaway. It was difficult to determine when the battery thermal runaway started without monitoring the cell surface temperatures. The burning of the battery casing produced a flame, and the fire suppression system was turned on. After the fire was extinguished, it was found that the battery pack did not catch fire at all. To ensure that the battery pack could undergo thermal runaway and catch fire, it was decided to remove the battery casing and monitor the battery cell temperatures. The thermal capacity of the water was utilized in cooling the flame and battery surfaces. The suppression nozzle was placed 1.5 m above the battery pack. For the dry chemical and class D powder suppression systems, the release time was between 35 and 50 s. For the water mist system, the flow rate was 3.6 gallons per minute (GPM), and the release time was 5 min. Lower flow rates and shorter release times for water mist were also used for studying the effects of water flow rate and release time on the battery fire suppression. Measured battery surface temperature data were collected by the data acquisition system in the trailer. The exit gas samples were processed using an infrared gas analyzer in the trailer to determine carbon monoxide (CO) and carbon dioxide (CO_2) concentrations. Cameras were used to observe and record the fire and suppression behaviors. Observations were made on a monitor in the trailer to determine the times for the first appearance of smoke and flame and the final extinguishment of the fire if there was one.

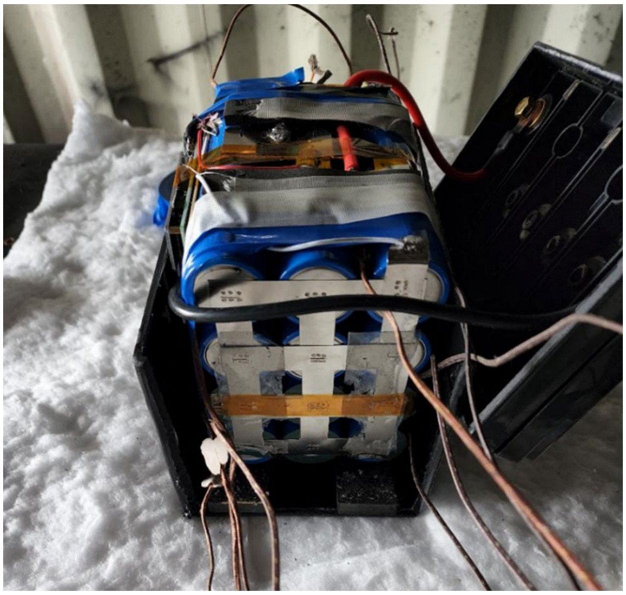
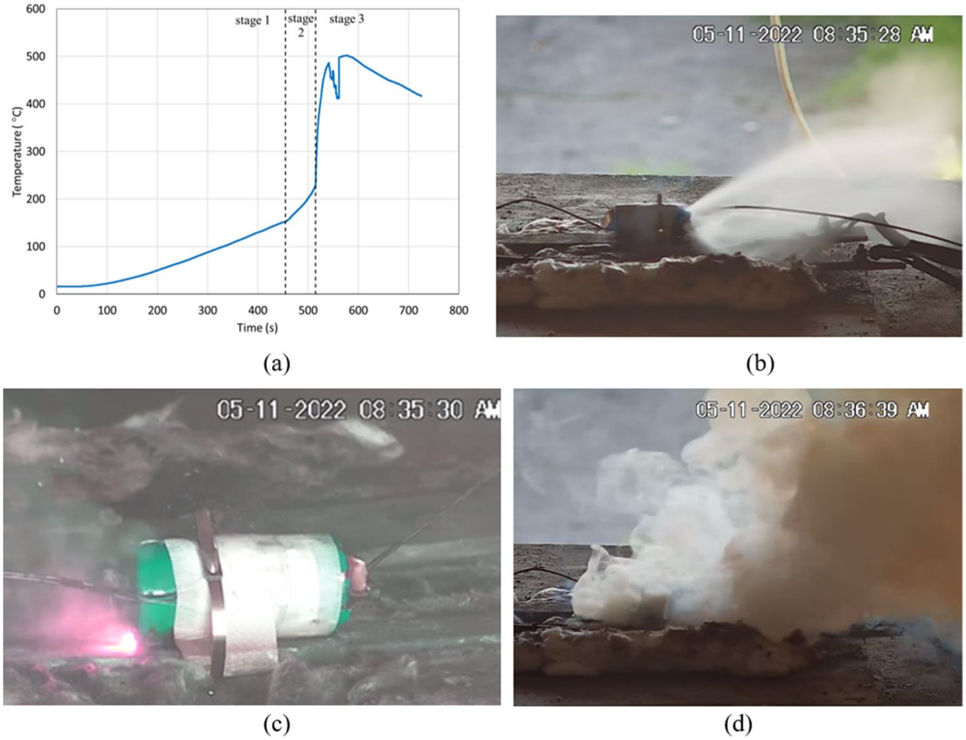


Fig. 2 LFP battery pack with thermocouples attached

3 Results and Discussion

3.1 Heating of a single Battery Cell

To better understand the fire suppression mechanism for the battery pack consisting of 24 cells, it is important to examine the fire behavior of a single cell first. A single battery cell was placed on the heaters, and two thermocouples were attached to the battery surface to monitor its temperature. The heaters were turned off when thermal runaway occurred. As shown in Fig. 3, the cell temperature increase can be divided into three separate stages. The first stage is a slow temperature increase. The cell temperature increased from ambient temperature to about 155 °C in 460 s, shown in Fig. 3a. During the second stage, the cell venting occurred, and the temperature increase accelerated. The third stage occurred at about 228 °C (515 s) when the thermal runaway started, and the temperature increased very quickly. Figure 3b shows the start of the cell venting (stage 2) with a large amount of gas released. Those vented gases are flammable, and a spark was produced when the gases encountered the heater as shown in Fig. 3c, indicating the condition was not favorable for a fire because the gas concentration was below the lower flammable limit. After about 1 min, a



(a) (b)

(c) (d)

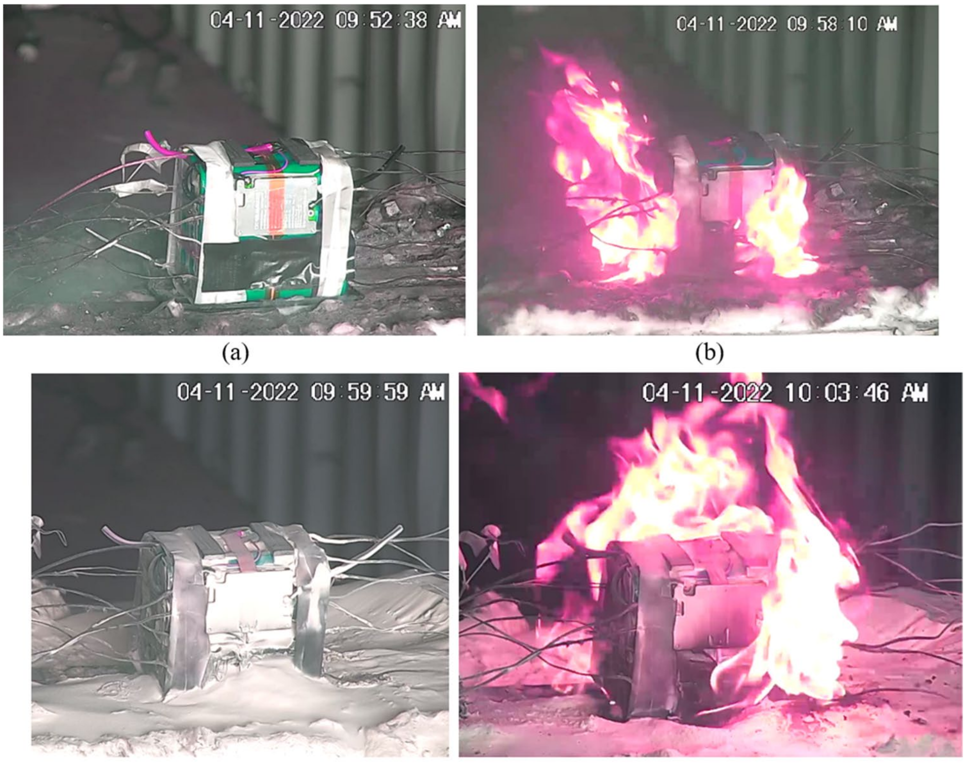
Fig. 3 Three stages of heating a single cell. **a** Cell temperature; **b** start of cell venting (stage 2); **c** spark produced from cell venting (stage 2); **d** start of thermal runaway (stage 3)

larger amount of smoke was released as shown in Fig. 3d indicating the start of thermal runaway (stage 3). It is interesting to note that when the cell temperature reached about 540 °C, there was a quick drop to 412 °C. This temperature is close to the methane ignition temperature, indicating that the use of such batteries in gassy coal mines should not be allowed if no mitigation measures are in place. After that, the temperature quickly increased again. This phenomenon has not been reported in the literature. On the camera, no clear difference was observed except continuous smoking.

3.2 Battery Fire Suppression Using Different Suppression Agents

Battery pack fire suppression tests were then conducted with different suppression systems. Figure 4 shows a typical battery fire and suppression process with the dry chemical suppression system. After about 3–4 min of heating, smoke appeared near the bottom of the pack produced from the venting of cells in contact with the heaters as shown in Fig. 4a. Smoking eventually changed to a flame after about 5 min as shown in Fig. 4b. The heaters were turned off, and the suppression system was turned on 1 min after the flame first appeared. With the release of dry chemical, the flame was extinguished quickly, and everything was covered by the white powder as shown in Fig. 4c. However, a reignition occurred after a few minutes as shown in Fig. 4d because the dry chemical was not able to sufficiently cool the battery to stop the internal exothermic reactions. The battery continued to burn all the way to self-extinguishment. Figure 5a shows the surface temperatures of two perimeter cells on the second row from the bottom of the pack shown in Fig. 4a, one on the left side and one on the right side. The surface temperature of the cell on the left reached near 600 °C, and then was reduced to 30 °C as the flame was extinguished. After about 2 min, both surface temperatures started to increase as reignition occurred. Figure 5b shows the exit gas analysis for CO_2 and CO. The CO_2 concentrations measured in this study were the values above the background value in ambient air. In this study, CO and CO_2 concentrations were diluted by the ventilation airflow. Because of the safety concern, the ventilation velocity was set at 0.2 m/s. Small concentrations (50 ppm for CO_2 and 2 ppm for CO) were present from the flame before activating the suppressant, and much higher concentrations occurred during reignition (400 ppm for CO_2 and 13 ppm for CO), indicating intensified burning of the battery after the reignition.

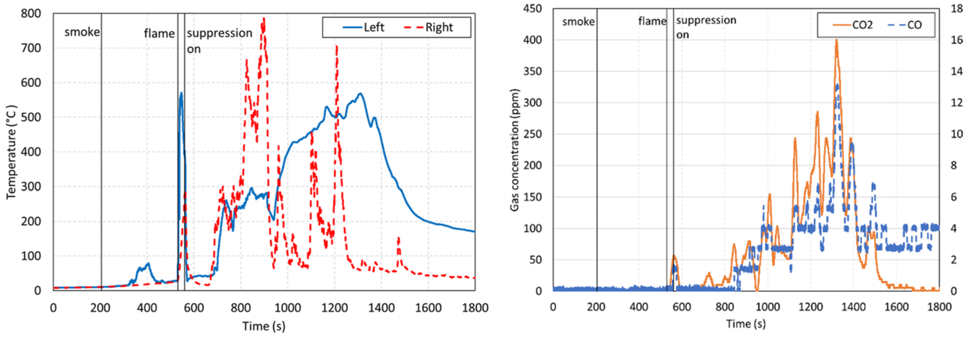
The same test procedure was used for the water mist suppression system. Figure 6a shows the smoking of the battery, and Fig. 6b shows the flame before the release of water mist. The water mist was turned on after the heater was turned off, and the flame was well established. Unlike the dry chemical suppressant that smothered the fire uniformly and quickly, the water mist needed a longer release time to extinguish the fire through cooling the flame and battery surface. It took about 85 s for the mist to extinguish the fire. The mist was kept on for 5 min, and no reignition occurred as shown in Fig. 6c. Both the right and left side cell surface temperatures



(a) (b)

(c) (d)

Fig. 4 Battery fire suppression using dry chemical: **a** smoking at left side; **b** flame before suppression was on; **c** flame was off after release of dry chemical; **d** reignition occurred



(a) (b)

Fig. 5 Cell temperatures (**a**) and exit gas concentrations (**b**) with dry chemical system

are shown in Fig. 7a, indicating no temperature rise after extinguishing the flame. The CO_2 concentration reached a peak value of about 90 ppm before the application of suppressant and returned to ambient concentration indicating no reignition occurred (Fig. 7b). The CO concentration was around zero. As the flame was extinguished quickly by water mist, the fire was significantly smaller compared to the fire in the suppression test using dry chemical. In that test, the maximum CO_2 value reached 400 ppm, while the maximum CO value was 13.5 ppm.

Class D extinguishment powder was also tested for suppression of the battery pack fire. Class D powder was not able to extinguish the flame quickly, and the battery continued to burn all the way to self-extinguishment. Figure 8 compares the typical cell surface temperatures and CO_2 concentrations for the three suppression systems indicating water mist is the best method to extinguish the Li-ion battery fire. With the application of the Class D powder, the fire reignited earlier and burned more intensely with greater peak CO_2 concentrations as compared to the dry chemical system.

3.3 Effect of Activation Time

To extinguish a fire quickly and effectively, it is important to activate the fire suppression system at a proper time. In general, it is better to activate the suppression system earlier. In practice, a fire suppression system is usually activated

Fig. 6 Battery fire suppression using water mist. **a** Smoking of battery; **b** flame before suppression was on; **c** complete extinguishment

Fig. 7. **a** Cell temperatures and **b** exit gas concentrations with water mist system

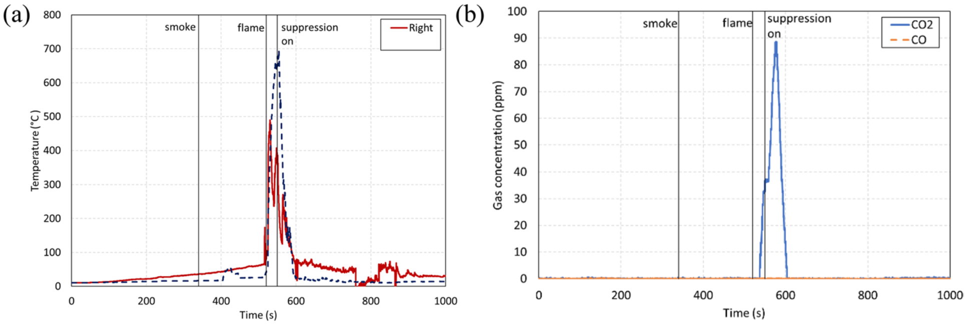
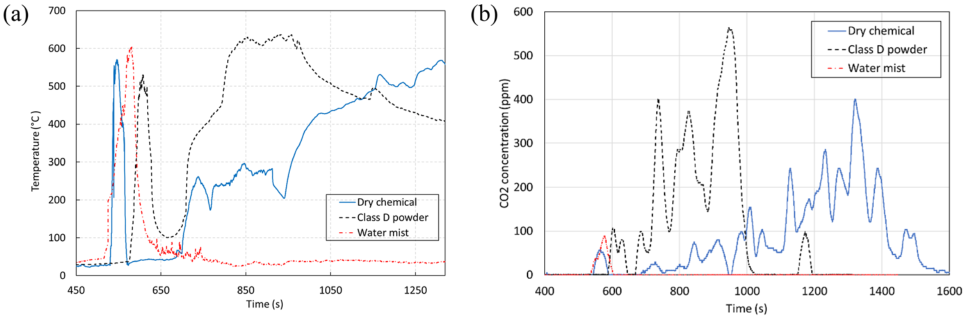


Fig.8 **a** Comparison of cell temperature and **b** CO_2 concentration for three suppression systems



through some kind of detection of an early fire indicator such as temperature rise, gas emission, or the flame itself. In this study, the fire suppression systems were activated manually, and this provided an opportunity to study the effect of activation time. As demonstrated by the test results, water is the better suppression agent compared to the dry chemical and class D powder. Therefore, water mist was used to investigate the effect of activation time. Four different activation times were used in the study including (1) 3 min after the first indication of smoke, (2) right at the first flame, (3) 30 s after the first flame, and (4) 1 min after the first flame. Three minutes after smoke simulates a typical thermal detector that usually activates 3–5 min after first smoke. Zero second after flame indicates that the flame is detected immediately. Thirty seconds after flame simulates the flame detection with a time delay to minimize false alarms. one minute after flame is used to examine whether a prolonged activation can affect the fire suppression. The performance of fire suppression sensors will be investigated in another study. The test procedure was the same as the previous suppression tests. In each test, the mist was released for 5 min. Table 1 summarizes the test results for different activation times.

When the water mist system was activated 3 min after the first smoke, it cooled the battery, and the maximum battery surface temperature was 106 °C. The peak CO_2 concentration at exit was 5 ppm. Thermal runaway was not reached, and no flame ever occurred. This result indicates that if battery cooling can start before it reaches thermal runaway, the battery fire might be prevented. With the activation times of 0, 30, and 60 s after the first flame, the peak CO_2 concentration increased with activation time. The battery also burned a longer time resulting in increased extinguishing time. The maximum cell temperature increased as the activation time increased from 0 to 30 s and decreased as the activation time increased from 30 to 60 s. These results indicate that earlier activation of the suppression system can reduce the extinguishing time of the battery fire significantly. No changes to ventilation flow or ventilation inversion were observed in the test facility during these tests.

3.4 Effect of Release Time

As demonstrated in Sect. 3.2, water is the best method out of the three suppression systems tested in this study. The major reason is that the release time for the dry chemical and class D powder systems was around 35–50 s, and therefore, these two systems could not sufficiently cool the Li-ion battery to prevent reignition. The release time for the water mist system was 5 min, so the battery was continuously cooled down to prevent the reignition. The release time is important not only for the dry chemical and class D powder systems but also for the water mist system. In this study, battery fire suppression tests were conducted to investigate the effect of the release time on the effectiveness of suppression. In all tests reported so far, a 5-min release time was able to prevent the reignition. One test was done to turn off the water mist immediately after the flame was extinguished. After only 20 s, reignition occurred and the fire burnt for more than 10 min. Although the battery reignited, it did not burn as violently as the reignition with the dry chemical, probably because of the cooling from water mist before the flame extinguishment. This can be supported from the comparison of CO_2 values shown in Figs. 5b and 9. In another two tests, the water mist was activated for a total of 3 and 5 min, respectively. There was no reignition in these two tests. The results indicate that if water is turned off immediately after flame extinction, it cannot prevent the reignition. If the water is on for 3 min or longer after flame extinction, it is able to prevent the reignition under the conditions in this study. Said et al. [18] investigated suppression of 18,650 Li-ion battery cell array fires with water mist and found that suppression of flaming combustion is not sufficient to stop cascading failure and the array must be continually cooled with water mist until the temperature of the cells is decreased below a certain threshold. This is consistent with the results of this study.

3.5 Effect of Water Flow Rate

The flow rate of water mist used in the water suppression tests was 3.60 GPM. To examine the effect of water flow rate on the effectiveness of fire suppression, the lower flow

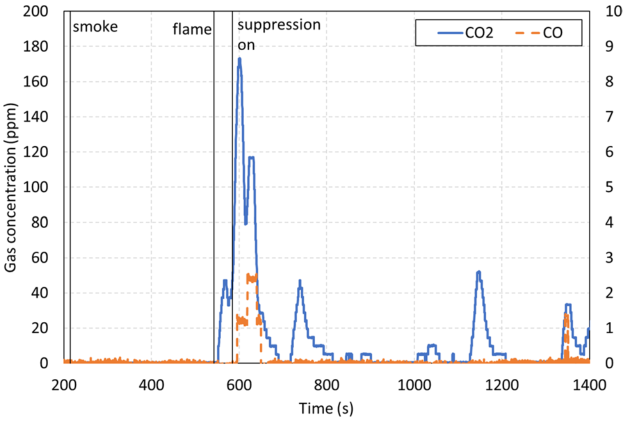


Fig. 9 Exit gas concentrations for the test where water was turned off immediately after the flame was extinguished

Table 1 Suppression results for different activation times

Activation time	Thermal runaway	Maximum cell temperature (°C)	Peak CO_2 concentration (ppm)	Extinguishing time (s)
3 min after smoke	No	106	5	No flame
0 s after flame	Yes	446	80	30
30 s after flame	Yes	696	89	86
1 min after flame	Yes	547	135	108

rates of 2.06 and 1.44 GPM were used for the same battery fire tests. With both flow rates, the fire was extinguished effectively without a reignition. Due to limitations of the water suppression system, it was not possible to further reduce the water flow rate to a value that the water mist system could not suppress the battery fire, as Wang et al. [2] reported in their experiments because of low water flow rate. However, these results demonstrate that with water mist, it is possible to achieve a sufficient suppression result using lower water flow rates. The actual amount of water needed to extinguish a BEV fire depends on many parameters such as battery size, battery chemistry, battery failure mode, battery pack construction fixture, and fire suppression strategies. This amount can vary significantly as it was reported by NTSB [12] that the total amount of water used to suppress high-voltage Li-ion battery fires ranged from 300 to 20,000 gallons.

4 Conclusions

Fire suppression experiments in this study were conducted for LFP Li-ion battery packs using dry chemical, class D powder, and water mist systems. The experimental results demonstrate that water was more effective in extinguishing the battery pack fires than dry chemical and Class D powder. With dry chemical and class D powder, the flame was extinguished temporarily, but reignition occurred after the suppressant was exhausted in less than 50 s. With water mist released for 5 min, the fire was extinguished, and no reignition occurred because of sufficient cooling provided by the water.

The effects of activation time, release time, and flow rate for the water mist system were investigated to explore the potential for battery fire suppression with limited water supply in underground mines. The experimental results indicate that earlier activation time of the suppression system could reduce the extinguishing time of the Li-ion battery fire, and a certain release time and subsequent quantity of water were needed to prevent the reignition of the battery fire. For the LFP battery packs tested in this study, release time was about 3 min. Water mist provides a potential to extinguish the battery fire using lower flow rates and therefore smaller amounts of water. In this study, when water flow rate was reduced by 60%, it was still able to extinguish the battery fire and prevent ignition.

Although suppressants were applied to exposed battery cells in this study, it allowed for examining the direct interactions between a Li-ion battery fire and suppressants through monitoring cell surface temperatures and observing the effects of the release of suppressants on the flames. It also removed the influence of the burning of combustible battery casing material on the initiation and development of the battery fire. The results from this study can serve as the knowledge base and lay the foundation for the battery suppression tests in a real situation with a battery enclosure in place.

5 Limitations

The exploratory research presented in this publication is focused on assessing the performance of fire suppression agents that may potentially be used when responding to lithium-ion battery thermal runaway scenarios in underground mines. A limitation of the study is focused on the sample size of agents and specific products selected to assess the performance and applicability to mine environment conditions. The study did not evaluate an exhaustive list of different types of suppression agents nor a valid sample size of products within each type. Furthermore, the study only focused on the performance criteria to suppress thermal runaway events and no considerations were made to assess the health and environmental impacts of any of the products tested. The conclusions drawn from this study speak to the performance of the limited number of agents tested and should not be construed as product endorsement nor recommendations for use in similar scenarios.

Data Availability Data is available upon request.

Declarations

Conflict of Interest The authors declare no competing interests.

Disclaimer The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by NIOSH.

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