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Comparison of Fire Suppression Techniques on Lithium-Ion Battery Pack Fires

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Abstract
Lithium-ion battery pack fires pose great hazards to the safety and health of miners. A detailed experimental study has been conducted at the National Institute for Occupational Safety and Health (NIOSH) Pittsburgh Mining Research Division (PMRD) to investigate the effectiveness of different fire suppression systems on Li-ion battery pack fire extinguishment. Tests were conducted in a well-ventilated container. Two sizes of battery packs (12 V, 24 V) were heated by heater strips to trigger thermal runaway and fire. Water mist with different flow rates, ABC powder, type D dry chemical, and water mist with F500 additives were used as the fire suppression agents. Multiple thermocouples were installed on the battery packs to measure the temperature evolution during the tests. The results indicated that the water mist with F500 additives is the most effective suppressant among the agents tested. Dry chemicals, however, do quench the fire for a moment, but cannot prevent re-ignition of the battery since they do not provide enough cooling. The findings of this paper can be used to develop safer battery fire suppression techniques in mining environments.

Keywords Lithium-ion battery · Fire suppression · Water mist · Dry chemical

1 Introduction

As an important alternative to fossil fuels, lithium-ion (Li-ion) batteries have seen their applications growing from consumer electronic products to large electric vehicles. In the mining industry, Li-ion battery powered electric vehicles (BEVs) are believed to be a promising replacement for diesel-powered vehicles whose emission of diesel particulate matter (DPM) is a major concern to the safety and health of miners [1]. The introduction of BEVs into the mining industry has not been trouble-free as the potential use of Li-ion BEVs in gassy underground mines escalates the fire and explosion risks [1]. Methane-air mixtures are found in many types of mines, and the energy released by a Li-ion battery during thermal runaway or accidents resulting in fire can be an ignition source for such mixtures [2, 3]. A safer and more reliable design and application of Li-ion BEVs could help reduce and mitigate the risk of fire and explosion accidents underground. The size of a battery pack fire can be indicated by the heat release rate (HRR). Wang et al. [4] used cone calorimetry tests and found that the peak HRR and total heat release increase with state of charge of the battery. Most of the HRR measurement of battery fires used the oxygen consumption theory [5, 6].

While preventing the fire and explosion of Li-ion batteries from occurring is necessary, suppression of such incidents when they occur is just as vital [7, 8]. In a mining environment where fire suppression resources are limited, an effective battery fire suppression technique is critical to the safety and health of miners. Numerous studies have been conducted to investigate the effectiveness of traditional fire suppression techniques on battery or battery pack fires. Unlike traditional fire suppression, battery fire suppression requires extensive cooling even after the fire is visually quenched [9-12] to reduce battery temperature and prevent re-ignition due to chemical reactions inside the batteries. Liu et al. [13] found that water mist can well control the thermal runaway of a battery by cooling the battery below a certain critical temperature. Larsson et al. [14] reported that the effectiveness of water mist on battery fire suppression is not obvious, and that hydrogen fluoride concentration increased after the application of water mist. Blum et al. [15] conducted large-scale

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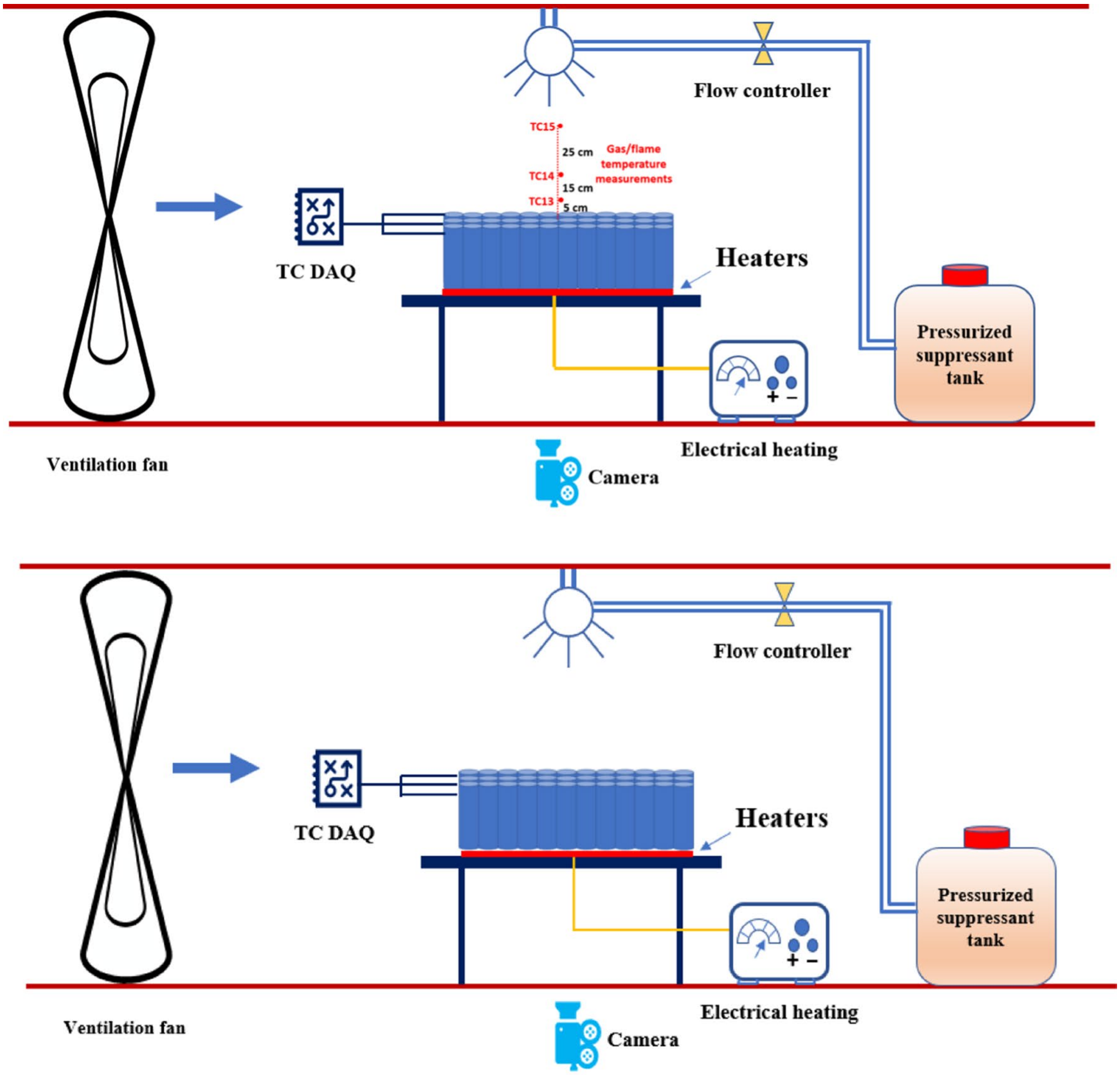
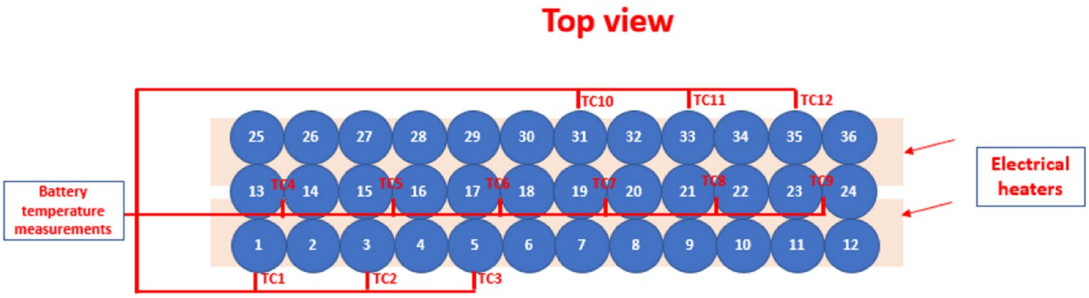


a. Test setup in the facility



b. Top view of measurement on battery pack

Fig. 1 Battery fire suppression test setup

Table 1 Test conditions

Test number	Battery size	Agent
1	12 V	Free burn
2	12 V	Water mist, 3 GPM
3	12 V	Dry chemical
4	24 V	Free burn
5	24 V	Water mist, 3 GPM
6	24 V	Dry chemical
7	12 V	Water mist, 1 GPM
8	12 V	Water mist, 2 GPM
9	12 V	Water mist 3 GPM with F500 additive

battery fire suppression tests and noticed that a large amount of water is needed to extinguish BEV fires. Research on effective fire suppression technique for small and large battery pack fires in a mining environment is limited.

In this work, detailed experimental research was conducted to investigate the effectiveness of different fire suppression systems on Li-ion battery pack fires. Two sizes of Nickel/Manganese/Cobalt (NMC) Li-ion battery packs and five fire suppression systems were chosen. Results of the fire suppression tests will be discussed and compared.

2 Experiments

Experiments were conducted within an open-ended shipping container (12.2-m length by 2.4-m width by 2.9-m height) located at the Pittsburgh Mining Research Division. Two types of Li-ion battery packs were used for the tests: a 12 V, 30Ah battery pack composed of 36 NMC cylindrical 18,650 batteries and a 24 V, 40Ah battery pack composed of 72 NMC cylindrical 18,650 batteries. Two 750-W electric-controlled metal heater strips with dimensions of 45 cm × 3.8 cm × 0.8 cm (length × width × thickness) were placed under the battery packs to induce thermal runaway. K-type thermocouples were attached on the battery pack to measure the battery temperature (as shown in Fig. 1). Several fire suppression systems were used for the tests. Each used a flow controller and suppression spray placed 0.5 m above the battery pack. Video cameras were used to record the fire and suppression behaviors.

The battery tests included free burn and the use of fire suppression agents: water mist (1, 2, 3 gallon per minute (GPM) and 3 GPM with F500 additive), ABC powder, and type D sodium chloride (NaCl) dry chemical. During the tests, the battery pack was placed on the two electric heater strips to induce a thermal runaway and trigger a fire. Timing information for the first visible release of smoke and fire was noted. Electrical heating was turned off after the first jet of fire was observed; suppression, if used, was initiated at the same time. Table 1 summarizes the test conditions. Fire and smoke behaviors were observed and noted throughout the tests. A low-speed ventilation (~ 0.5 m/s) was applied to clear the smoke and gases.

3 Results and Discussion

With temperature measurements, comparisons were made between the free burn case and the suppression cases with distinctions drawn after suppression was applied to the battery pack fire.

3.1 Free Burn versus Water Suppression

Test 1 is the free burn case where no suppression was applied. In this case, smoke was observed to release at about 3.5 min after heating started, and the flame started at about 10 min. The explosion and fire continued for about 8 min before the battery pack burnout. During the test, it was observed that some of the batteries exploded and ejected from the pack, which is a potential ignition source for other combustibles nearby. Figure 2 shows the four sequences

Fig. 2 Four sequences of free burn of a 12 V battery pack fire (**a** smoke starts, **b** flame starts, **c** explosion, **d** burnout)

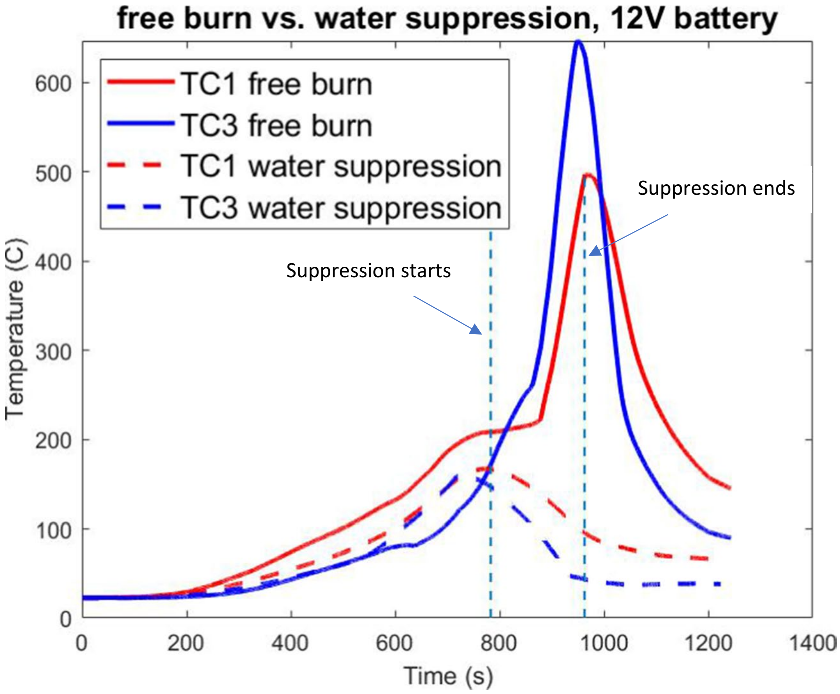
Fig. 3 Three sequences of water mist suppression of a 12 V battery pack (**a** flame starts, **b** water suppression starts, **c** extinguishment)

of the free burn for the battery pack starting from smoke emission to battery burnout. As shown in the images, most of the batteries were completely burned out. However, it is worthwhile to note that some of the batteries were not burned even after the test was over due to the explosion and shootout behaviors. Some temperature measurements of the batteries were invalid due to the shootout behavior.

Test 2 is the water mist suppression with 3 GPM flow rate. In this case, smoke was observed to release at about 3 min after heating started, and the flame started at about 10 min. Heaters were unplugged at about 10.5 min. Water suppression started at about 13.5 min when the flame was fully established. Water suppression was turned off at about 16.5 min and the battery pack fire was completely extinguished. Re-examination of the battery pack after the test revealed that 8 batteries fully burned or exploded, but 28 of the batteries were partially burned or remained intact. There was no re-ignition after the battery fire was extinguished. Figure 3 shows the sequences of the water mist fire suppression

Temperatures were compared between the free burn of a 12V battery pack and a burn with water suppression. Figure 4 shows the temperature history of two temperature measurements. The two vertical dashed lines represent the water suppression period. It was observed from Figure 4 that battery temperatures of the free burn tests were much higher than the water mist suppression tests. In the free burn case, batteries went into thermal runaway and caught fire with sharp increases in battery temperatures. In the water suppression case, after water suppression was applied, the two thermocouple temperatures quickly dropped and remained below 200°C for the rest of the test. No re-ignition was observed. The cooling effect of water suppression was probably the key in containing the fire and preventing re-ignition.

Fig. 4 Temperature comparison of free burn and water mist suppression



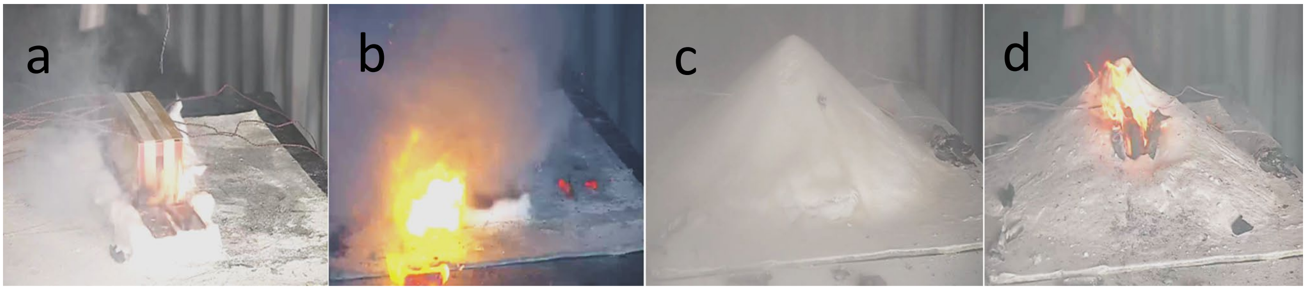


Fig. 5 The sequences of NaCl dry chemical suppression (**a** flame starts, **b** suppression starts, **c** battery fire quenched, **d** re-ignition and explosion)

3.2 Free Burn versus Dry Chemical Suppression

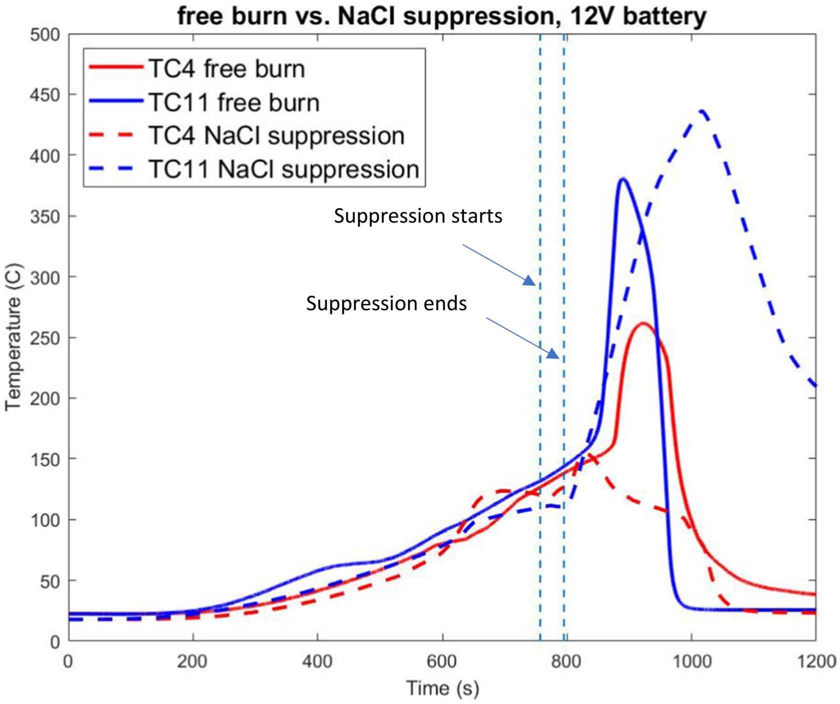
Test 3 is a fire suppression case with type D dry chemical. In this case, the battery fire started at about 10.5 min after heating. The suppressant was discharged at 12.5 min and lasted for about 45 s before the suppressant was depleted. The battery pack was buried under the dry chemical, and the fire visually disappeared as shown in Fig. 5 c. Shortly after the fire was quenched, re-ignition occurred, then the explosion followed. The battery fire continued until burnout. In this case, the dry chemical was able to quench the fire temporarily but failed to extinguish the fire completely.

The temperatures were compared between the free burn of a 12V battery pack and a burn with type D NaCl dry chemical suppression. Figure 6 shows the temperature history of two temperature measurements. The two vertical dashed lines represent the dry chemical suppression period. For the suppression case, it was observed that after suppression was applied, battery temperatures had a noticeable drop before they went up again due to re-ignition. In this case, the lack of cooling effect afforded by the dry chemical application probably played a major role in the re-ignition as the chemical reactions inside the battery continued despite external flame quenching and air exclusion.

3.3 Large Size Battery Pack

Test 4 is a free burn of a large battery pack (24V), test 5 is a water mist suppression case of the large battery pack (24V) fire with 3 GPM flow rate, and test 6 is the ABC dry chemical suppression case of the large battery pack (24V) fire. Figure 7 shows the comparison of free burn with water mist suppression and ABC dry chemical suppression regarding battery temperatures. The vertical dashed lines in both figures represent the suppression period. In the water mist suppression case (Fig. 7a), the application of water

Fig. 6 Temperature comparison of free burn and dry chemical suppression



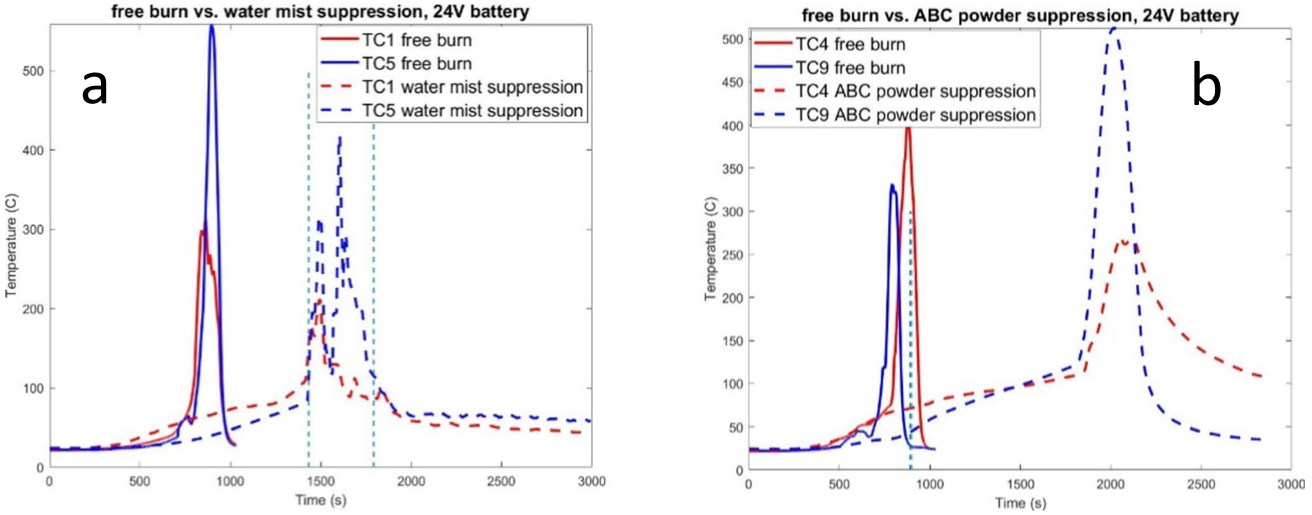


Fig. 7 Comparison of free burn of large size battery pack with suppressions: **a** 3 GPM water mist suppression, **b** ABC powder suppression

slowed the heating, but fire and explosion occurred during the suppression period. The 3 GPM water mist failed to suppress the fire of large size battery pack. In the ABC dry chemical suppression case (Fig. 7b), the initial application put out the flame temporarily, but battery temperatures still climbed slowly and eventually fire and explosion followed. The dry chemical also failed to contain and suppress the large battery pack fire.

3.4 The Effect of Water Mist Flow Rate

Different flow rates of water mist suppression were also used to study their impact on the small battery pack fire. Test 7 used water mist at 1 GPM, test 8 used water mist at 2 GPM, and test 9 used water mist at 3 GPM with F500 additive. In all three of these tests, water mist suppression started when the first explosion was observed. Four thermocouple data were plotted to demonstrate the battery temperature evolution against the time, shown in Figure 8. It was observed that

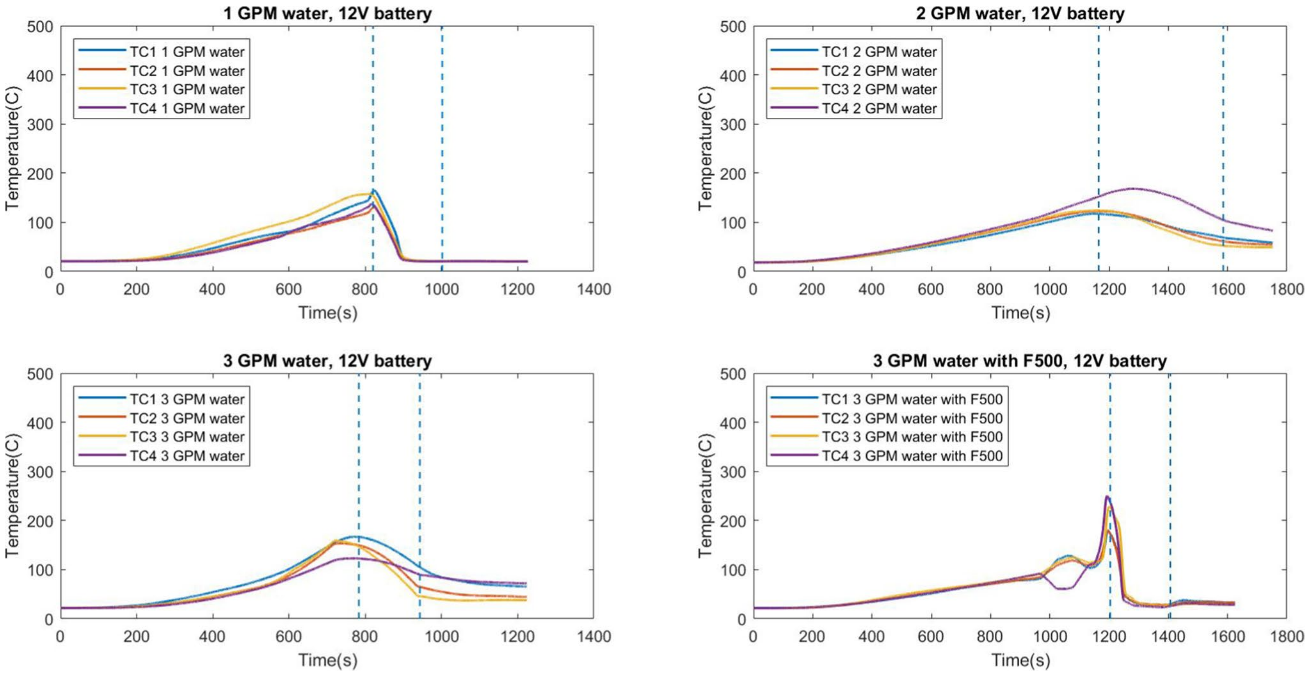


Fig. 8 The effect of water mist flow rate on suppression

water mist of all three flow rates can contain and suppress the small size battery fire without re-ignition. The 3 GPM flow rate with F500 additive might be the most effective since the drop in temperature was the quickest and most significant decrease.

4 Conclusions

Battery pack fire suppression tests were conducted at the NIOSH Pittsburgh Mining Research Division as part of its continual effort to develop workplace solutions to reduce the risk of mine disasters and mine workers' risk of injuries and fatalities. Water mist with different flow rates and/or additives, type D NaCl, and dry chemical ABC powder were used to study their effectiveness in Li-ion battery pack fire suppression. The results indicated that water mist can suppress a small battery pack fire, and its cooling effect prevents re-ignition from occurring. Water mist suppression with F500 as an additive can better suppress the fire. Type D NaCl and dry chemical ABC powder fire suppressants could quench the battery pack fire temporarily but failed to cool the battery, and re-ignition occurred. The results from this study can be used to develop an improved Li-ion battery pack fire suppression system for a mining environment.

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Declarations

Disclaimer The findings and conclusions in this paper 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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