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Optimization of Fire Suppression Nozzle Location on Simulated Mobile Mine Equipment

Wei Tang
CDC NIOSH, Pittsburgh, PA

Richard Thomas
CDC NIOSH, Pittsburgh, PA

Davood Bahrami
CDC NIOSH, Pittsburgh, PA

Liming Yuan
CDC NIOSH, Pittsburgh, PA

ABSTRACT

The location and orientation of fire suppression nozzles is critical in suppressing mobile mine equipment fires. To effectively suppress such fires, optimization needs to be considered for the suppression nozzle locations and discharge angle. Detailed experiments were conducted to study the effectiveness of fire suppression agents with different nozzle configurations. A variety of fire suppression systems including dry chemical, wet chemical, dual agent (dry and wet chemical), carbon dioxide, and water mist were used. Six types of nozzle locations were studied, and their fire suppression effectiveness were compared. Results from this work highlight potential considerations when determining effective fire suppression designs.

INTRODUCTION

Mineworkers frequently confront the peril of mine equipment fires, which can erupt in both surface and underground mines, often resulting in injuries or fatalities. The efficacy of fire suppression systems installed on such equipment may be hampered by deficiencies in design and installation practices. A significant portion of reported mine fires stem from equipment malfunctions, notably ignitions of combustible fluids like hydraulic fluid leaking onto heated engine surfaces due to hose ruptures. To curtail the incidence of equipment fires, it is imperative to devise robust measures aimed at mitigating or forestalling hot surface ignitions on mining machinery. Enhancing fire suppression techniques for equipment fires is vital for safeguarding equipment operators against fire-related injuries and fatalities. Despite the inclusion of fire suppression systems in certain mining equipment, their effectiveness is often compromised by subpar design, inadequate installation, and potential damage from fire if not promptly activated [1].

A variety of fire-extinguishing agents, including dry chemical, wet chemical, carbon dioxide, water mist, and foam, can be employed within a fire suppression system. The effectiveness of each agent varies depending on factors such as the type of fuel involved, fire location, available fuel quantity, and surrounding ventilation. Major mechanisms for fire suppressi`on encompass cooling, fuel separation or removal, oxygen dilution, and disruption of the combustion chain reaction. Each fire-extinguishing agent targets one or more of these mechanisms. Dry chemical agents, typically composed of a non-conductive powder mixture, are used extensively for suppressing mine fires. Wet chemical agents, comprising a blend of organic and inorganic salts in solution, were initially developed for cooking-oil fires and can create a temporary foam layer atop flammable liquids to facilitate cooling and prevent exposure to air. Carbon dioxide, a long-standing fire suppressing solution, is employed for suppressing flammable liquids, gas fires, and electrical fires by depleting oxygen, albeit with limited cooling capabilities.

The positioning of fire suppression nozzles is another critical parameter for their effectiveness in suppressing fires. Proper placement ensures adequate coverage of potential fire hazard areas and optimal discharge angles to target the fire source. Evaluating these factors may enhance the overall efficiency of fire suppression systems and reduce the risk of fire-related injuries, fatalities, and equipment damage. In this study, six configurations of fire suppression nozzle positioning were selected to investigate their respective impact on the suppression effectiveness, and a comparison is made to evaluate the optimal nozzle location and orientation for the conditions tested.

EXPERIMENTAL SETUP

Tests were designed to assess the influence of different nozzle locations and fire suppression agents in handling spray fires ignited by various flammable liquids like diesel fuel, motor oil, and hydraulic oil on a diesel engine. A modified steel shipping container serves as the designated test facility at the National Institute for Occupational Safety and Health (NIOSH) Pittsburgh Mining Research Division in Pittsburgh, Pennsylvania. The container measured 40 feet (12.2 meters) in length, 8 feet (2.4 meters) in width, and 9.5 feet (2.9 meters) in height, as depicted in Figure 1. To safeguard the wooden floor from ignition during tests, steel plates were installed over it. Ventilation control was facilitated by a 1-horsepower, 42-inch (1.07-meter) diameter variable-speed fan positioned at one end, while the opposite end remained open, allowing for adjustment of airflow up to 500 feet per minute (2.54 meters per second).

To gauge the gases emitted during the diesel engine fire trials, an infrared gas analyzer was employed. It measured carbon monoxide (CO) levels ranging from 0 to 5,000 parts per million (ppm), carbon dioxide (CO_2) levels ranging from 0 to 1 percent, and oxygen (O_2) levels ranging from 0 to 25 percent. The infrared gas analyzer's output voltage was converted to record the data on a laptop and visually represent it in real-time. Figure 2 shows

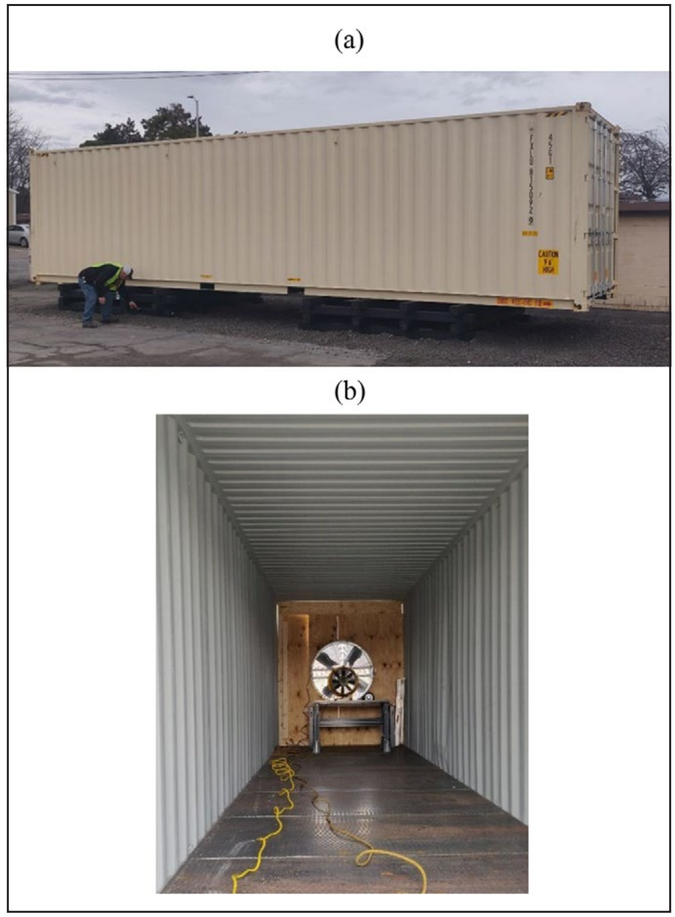

Figure 1. Steel shipping container (a) outside and (b) inside, modified to be used as a fire suppression test facility

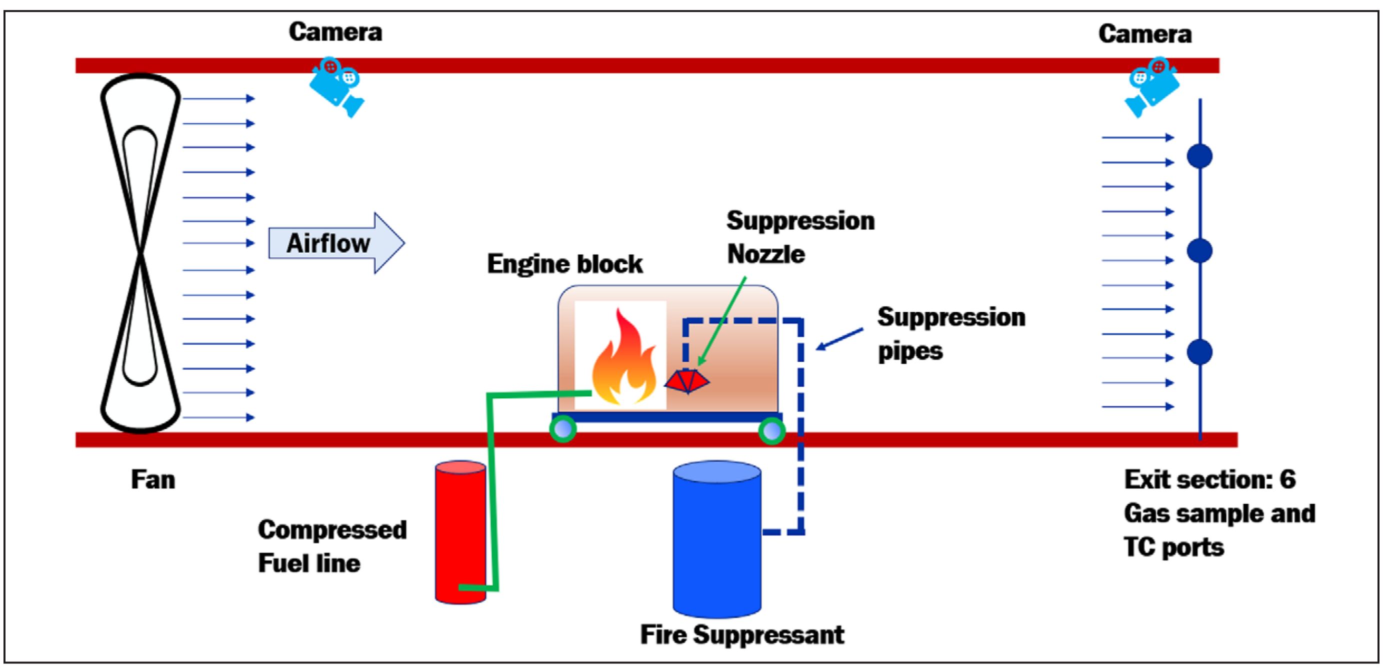

Figure 2. Schematic experimental setup

the schematic experimental setup. Gas temperatures at the container exit section were monitored using thermocouples (TC ports). A diesel engine block, measuring 53 inches (1.35 meters) in length, 23 inches (0.58 meters) in width, and 36 inches (0.91 meters) in height, was affixed to a steel frame equipped with casters, enabling easy maneuvering to the designated test location.

Suppression tests involved employing a liquid spray fire fueled by diesel, engine oil or hydraulic fluid. The delivery mechanism for these liquids was established using a compressed air cylinder equipped with a regulator to manage pressure. This system interfaced with a 1-gallon (3.8-liter) stainless steel cylinder containing various fuel types, delivered via ¼-inch stainless steel tubing to the fuel nozzle. Achieving a stable spray fire necessitated reaching specific threshold values for oil pressure and temperature. To facilitate this, an electric heating strip encircled the cylinder to elevate oil temperature and reduce viscosity, particularly when using engine oil and hydraulic oils. A pair of cameras were installed near the ceiling of the test facility to monitor the tests.

Six fire suppression nozzle configurations were used in the tests: 3 configurations for single agent systems, 3 configurations for dual agent systems. The detailed configurations are portrayed in Figure 3. A diesel engine block with dimensions of 53-inch (1.35-m) length, 23-inch (0.58-m) width, and 36-inch (0.91-m) height was mounted onto a steel frame with casters on it to have the ability to roll it into the correct location for the test. For single agent system tests, there was one suppression nozzle on each side of the engine block. For position A, both nozzles were aimed at the engine block. For position B, both nozzles were pointed at the fire source. For position C, one nozzle was pointed at the fire source while a second nozzle was pointed away.

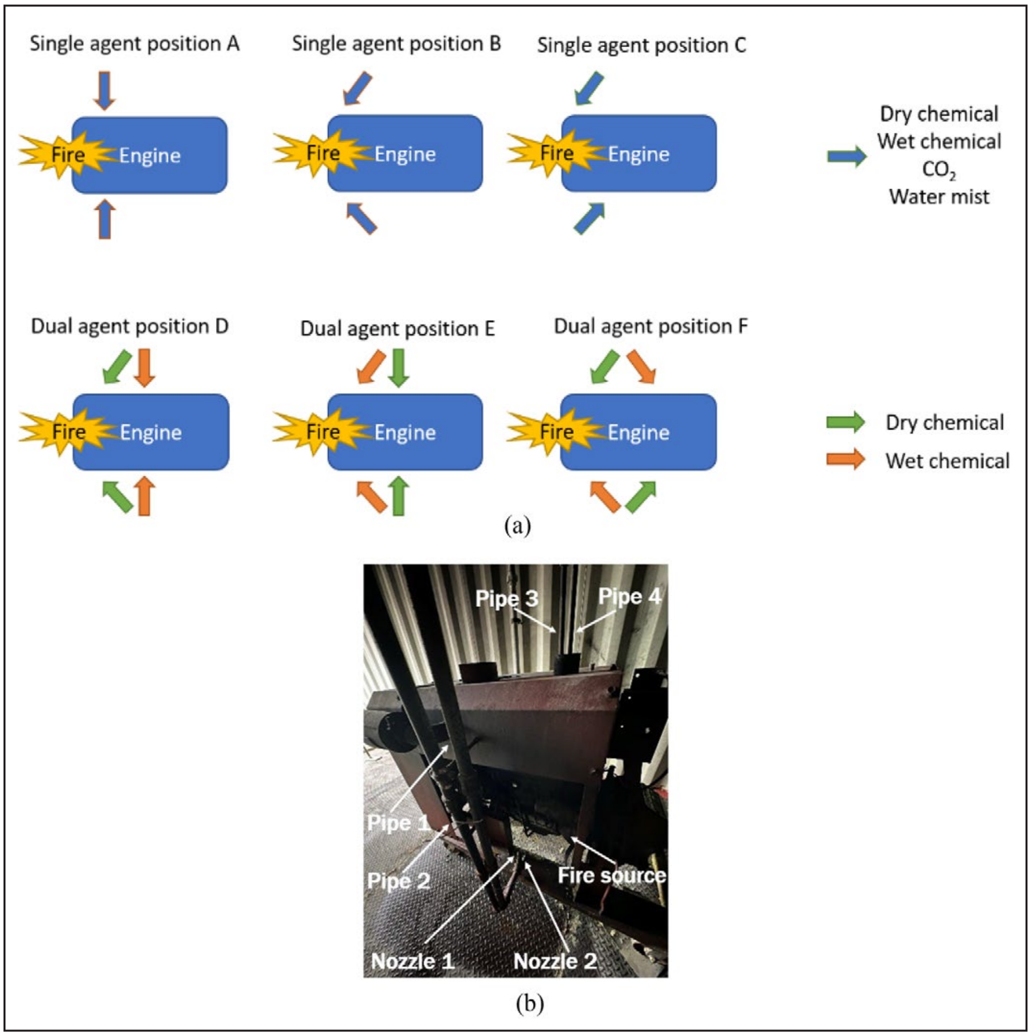

Figure 3. (a) Six nozzle location configurations and (b) photo of test set up with nozzle locations

The suppressants used in the single agent system tests were dry chemical, wet chemical, CO_2, or water mist. The dual agent system tests had 2 suppression nozzles on each side, one for dry chemical and one for wet chemical suppression agents, also shown in figure 3b. The suppressants used in the dual system were wet chemical and dry chemical, and they were released simultaneously, running through the pipes down to the nozzles.

EXPERIMENTS

The diesel engine block sat at a distance of 12 feet (3.66 meters) from the fan, positioned at the center of the Fire Suppression Facility. Before commencing the test, the fan was adjusted to achieve the desired airflow to remove the smoke from test area, approximately 145 feet per minute (0.74 meters per second) at the exit section. Airflow in front of the diesel engine was measured using a vane anemometer via a traverse method. Once the fan was set, no further adjustments are made. Data acquisition began 30 seconds before each test to capture baseline parameters. After recording baseline data, the fuel spray system was activated, igniting the fuel with a propane burner as it sprayed from the nozzle. The PJ20 spray fire nozzle [2], situated 3 inches (0.08 meters) in front of the diesel engine and 14 inches (0.36 meters) above the floor, atomized the fuel. This process was replicated for motor and hydraulic oils, with the addition of a heating strip wrapped around the cylinder to decrease viscosity so that adequate atomization and stable spray fire could be achieved.

The spray fire was allowed to burn until the concentrations of CO and CO_2 gases stabilized typically within 60 seconds, before activating the fire suppression system. Suppression nozzles were positioned at one of the six configurations. In one instance, a wet chemical fire suppressant agent was employed with the nozzle configuration A. The activation of the wet chemical suppressant agent was manually initiated from outside the Fire Suppression Facility. Once the fire suppression agent was fully discharged from the cylinder, typically within 45 seconds, and if the fire was successfully suppressed, the fuel continued to spray for an additional 20 seconds to test for potential reignition. If no reignition occurred, the fuel spray system was deactivated, marking the completion of a suppression test. However, if the fire suppression system failed to suppress the fire, the diesel fuel dispersal system was shut down, indicating a non-suppression test outcome.

At the exit section of the modified shipping container, a 6-point gas monitoring array was installed to measure the gas components generated from the fire. The two arrays consisted of ½-inch diameter PVC pipes positioned at the facility's center. Each pipe featured six 1/8-inch holes drilled along its vertical section to sample gases. These sampling points were vertically positioned at 53 inches (134.6 cm), 72 inches (182.9 cm), and 94 inches (238.8 cm) from the floor. A ½-inch tube connected these PVC pipes to the control room, leading to a set of infrared gas analyzers where the mixed gas was analyzed. The gas analyzers monitor CO, CO_2, and O_2 gas concentrations, collecting data every 0.1 seconds. The raw data underwent further analysis to accurately determine gas concentrations. A 6-point thermocouple array was positioned at the exit section to measure gas temperatures. These thermocouples were affixed to two vertical ½-inch diameter PVC pipes running from the floor to the roof, spaced at the same location as the gas sensors. Gas temperature data was recorded in the control room via the data acquisition system.

RESULTS AND DISCUSSION

Heat Release Rate (HRR) of a fire is a good indicator of the fire size and intensity, and in most cases, can be used to identify the stage of a fire, for example, the growth stage or decay stage, etc.

The method for calculating the HRR is based on the CO_2 and CO generation rates. With this method, the HRR is calculated from measured gas concentrations of CO, CO_2, and measured gas velocity [3]. The calculation is expressed as equation 1:

$$Q_A = \left[\frac{H_C}{k_{CO_2}}\right]\dot{m}_{CO_2} + [\frac{H_C - k_{CO}H_{CO}}{k_{CO}}\dot{m}_{CO} \quad (1)$$

where Q_A is the HRR, kW; H_C is the total heat of combustion of the fuel, kJ/g, and can be determined from the proximate analysis of the fuel; H_{CO} is the heat of combustion of CO, 10.1 kJ/g; k_{CO_2} is the stoichiometric mass of CO_2 produced per unit mass of the fuel; k_{CO} is the stoichiometric mass of CO produced per unit mass of the fuel; $\dot{m}_{CO_2}$ is the production rate of CO_2 from the fire, g/s; and $\dot{m}_{CO}$ is the production rate of CO from the fire, g/s; k_{CO_2} and k_{CO} are the fuel-dependent constants and can be calculated based on the experimental results from Egan [4] for different fuels.

For combustion of a fuel, the CO and CO_2 generation rates can be determined from their bulk-average concentrations downstream of the fire by the expressions:

$$\dot{m}_{CO_2} = VAr_{CO_2}CO_2 = 1.97 \times 10^{-3}VACO_2 \quad (2)$$

$$\dot{m}_{CO} = VAr_{CO}CO = 1.25 \times 10^{-3}VACO \quad (3)$$

where V is the exit average air velocity, m/s; A is the entry cross-section area, m^2; r_{CO2} is the density of CO_2, which is 1.97 kg/m^3. r_{CO} is the density of CO, which is 1.25 kg/m^3. DCO_2 is CO_2 gas concentration produced in the fire, ppm; and DCO is CO gas concentration produced in the fire, ppm.

Figure 4 shows the HRR comparison of two cases, one where the fire was fully suppressed, and the other was not (non- suppressed). For the suppressed case, a rapid drop in HRR is observed after the fire is put out. For the non-suppressed case, a temporary drop in HRR is observed which was probably due to a partial suppression of the fire. However, since the fire is not suppressed after the suppressant is depleted, the fire starts growing again as indicated by the increase in the HRR.

Figure 5 shows the temperature evolution of exit gas at different measurement locations. The gas temperatures are also identified in the figure corresponding to their distance from the floor and airflow rate in feet per minute (FPM). Similar to what was found on the HRR evolution, in the suppressed case, the gas temperature increases until the fire suppression is initiated. Once the suppression is initiated, the gas temperature drops to the pre-fire condition.

Figure 6 shows the temperature evolution of a non-suppressed case. The gas temperature first rises with fire, then it shows a temporary drop due to fire suppression, but since the fire was not suppressed, the temperature increases again after the suppressant is depleted.

The overall effectiveness results of the fire suppression tests are shown in Table 1. The effectiveness of the different tests was determined by the ratio between the number of suppressed cases to the number of total cases for each nozzle configuration. Results indicated that the single agent position A achieved the least effectiveness, below 50%. All other nozzle locations achieved an effectiveness over 70%.

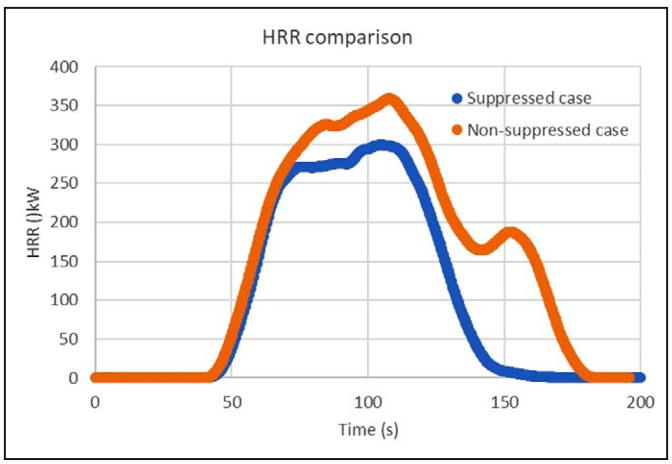

Figure 4. HRR comparison of suppressed and non-suppressed cases

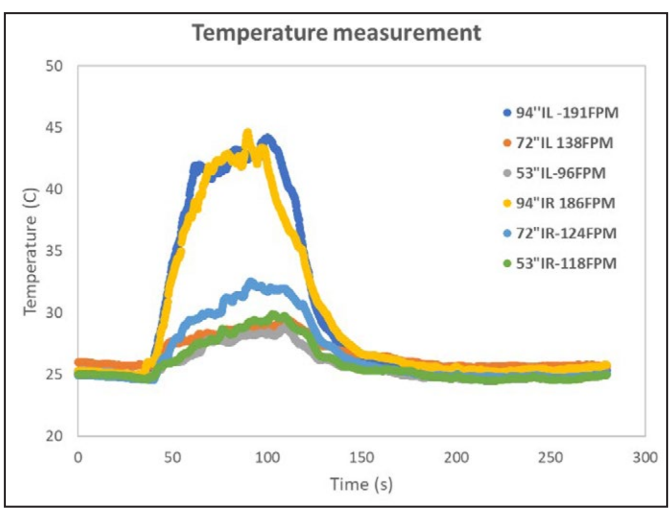

Figure 5. Temperature evolution of a suppressed case

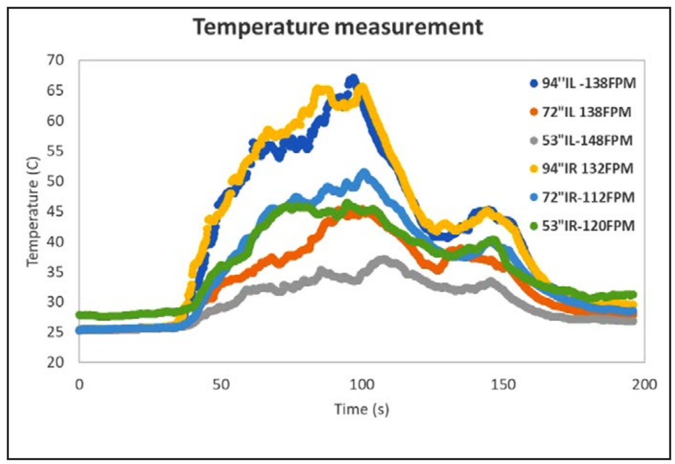

Figure 6. Temperature evolution of a non- suppressed case

Table 1. Test results of the fire suppression tests

Nozzle Location	Count of Not Suppressed	Count of Suppressed	Effectiveness [%]
Single agent position A	13	11	46
Single agent position B	2	22	92
Single agent position C	7	17	71
Dual agent position D	0	6	100
Dual agent position E	1	5	83
Dual agent position F	0	6	100

Dual agent positions D and E have the highest effectiveness, both at 100%.

Detailed comparisons are also made between the dual agent and single agent cases where dry chemical and wet chemicals were chosen as the fire suppression agent. Although dual agent cases used double the amount of suppressant than single agent cases, the effectiveness does not seem to improve much, which may suggest that picking the right nozzle locations and the right suppressant is critical to the success of suppression.

Tables 2, 3 and 4 show the breakdowns of the suppression effectiveness for nozzle locations A, B, and C separately. A few observations can be made:

1. For position A, the two nozzles are pointing at the engine block. CO_2 and wet chemical have very low suppression effectiveness, while dry chemical performs the best.
2. For position B, which consisted of the two nozzles pointing directly at the fire source, most of the fire suppression is successful, regardless of the suppressant.
3. For position C, which consisted of one nozzle pointing towards the fire source and one nozzle pointing away, most tests were successful with the exception of the cases employing the CO_2 fire suppression agent.

Table 2. Suppression effectiveness results for single agent position A

Suppressant Agent	Count of Not Suppressed	Count of Suppressed	Effectiveness [%]
CO_2	5	1	17
Dry chemical	0	6	100
Water mist	2	4	67
Wet chemical	6	0	0

Table 3. Suppression effectiveness results for single agent position B

Suppressant Agent	Count of Not Suppressed	Count of Suppressed	Effectiveness [%]
CO_2	0	6	100
Dry chemical	0	6	100
Water mist	0	6	100
Wet chemical	2	4	67

Table 4. Suppression effectiveness results for single agent position C

Suppressant Agent	Count of Not Suppressed	Count of Suppressed	Effectiveness [%]
CO_2	5	1	17
Dry chemical	0	6	100
Water mist	0	6	100
Wet chemical	2	4	67

If comparisons were made between the three positions for the same suppression agent, another interesting finding is that, for most of the nozzle location configurations, wet chemical seems to be the least effective agent in our suppression tests, while dry chemical is effective in every test. On the other hand, the effectiveness of CO_2 and water mist seem to be influenced by nozzle configuration.

CONCLUSIONS

A series of fire suppression tests were conducted on simulated mobile mine equipment with different suppression nozzle configurations and different fire suppressant agents. Two sets of nozzle location configurations, namely single agent systems and dual agent systems, were investigated to study the suppression effectiveness. The major findings can be concluded as follows:

1. For single agent nozzle location, position B is better than positions A and C. It indicates that when the location of the fire source is known, the suppression nozzle should be pointed at the fire source to achieve better effectiveness.
2. In most of the tests, dry chemical seems to be a better fire suppressant in spray oil fires.
3. Dual agent does not necessarily provide higher suppression effectiveness, picking the right nozzle locations and suppressant might be more critical.

These results are only applicable to the studied test conditions which are based on the fire not being 75% or more enclosed. However, it is expected that the lesser performing systems will perform better under total system flooding conditions where the fire is 75% or more enclosed.

LIMITATIONS

The results of this experimental research were limited to only provide scientific data for the purpose of fire suppression effectiveness. Because the tests were designed to evaluate five different fire suppression agents, using 6 distinct configurations, there are conditions that were not evaluated in this study. Location and orientation configurations were selected based on objective to evaluate performance using a consistent test set up and may not necessarily follow the installation guidelines set by individual fire suppression system manufacturers. Installation guidelines may impact the specific nozzle orientations, the type of dispersion nozzles, number of nozzles, separation distances, and amount of fire suppression agent recommended. Accordingly, it may be possible that the fire suppression agents may perform differently when installed on mobile mining equipment in real world applications. Additionally, no testing was done to evaluate any health or environmental impacts.

DISCLAIMER

The findings and conclusions in this report are those of the author(s) 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 an endorsement by NIOSH.

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