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Design of a water curtain to reduce accumulations of float coal dust in longwall returns

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Abstract

Accumulation of float coal dust (FCD) in underground mines is an explosion hazard that affects all underground coal mine workers. While this hazard is addressed by the application of rock dust, inadequate rock dusting practices can leave miners exposed to an explosion risk. Researchers at the National Institute for Occupational Safety and Health (NIOSH) have focused on developing a water curtain that removes FCD from the airstream, thereby reducing the buildup of FCD in mine airways. In this study, the number and spacing of the active sprays in the water curtain were varied to determine the optimal configuration to obtain peak knockdown efficiency (KE) while minimizing water consumption.

Keywords

Float coal dust; Longwall; Water spray; Knockdown efficiency; Explosion prevention; Dust control

1. Introduction

The accumulation of float coal dust (FCD) with a diameter ≤ 74 μm poses an explosion hazard to all underground coal miners [1–3]. These explosions typically occur when methane gas ignites and the resulting pressure wave re-entrains coal dust that was liberated by mining activities and has settled out of the ventilating air onto the floor, roof, and ribs of the mine entries. While the occurrence of dust-fueled explosions is relatively low–three recent instances occurred in 2001, 2006, and 2010–these represented 31%, 36%, and 60% of the underground coal mining fatalities for their respective years [4]. The current federal regulation requires that mines apply rock dust to mine entries in order to maintain a total incombustible content of 80%, which inhibits explosion propagation [5]. In the case of longwall mines, it may be possible to reduce the amount of FCD that settles in the mine airways by developing strategies to limit the amount of dust that is able to leave the active mining face.

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Historically, control of mining dust has been focused on reducing worker exposures to respirable dust, which is linked to coal workers' pneumoconiosis (CWP) and other chronic and acute health problems [6]. Respirable dust controls are designed with the sole purpose of keeping mine workers in clean air, and a targeted control can achieve this by moving dust-laden air away from miners, typically by face ventilation and open-air water sprays. However, for FCD controls to be effective, they must remove dust from the airstream. There have been extensive studies focused on understanding the effects of specific factors, such as operating pressure, orientation, ventilating airflow, droplet size, and spray nozzle type, on the knockdown performance of sprays in the presence of respirable dust [7–13]. While these factors have been shown to directly control droplet size, droplet frequency, and velocity, which affect the collision efficiency of the system, these findings needed to be verified with respect to FCD particles.

To close this knowledge gap, NIOSH conducted an investigation aimed at evaluating the efficiency of methods at reducing float dust concentrations in the general airstream. This study found that the guidelines for spray operation established for respirable dust held true when operating a spray with the goal of removing FCD [14]. Additionally, it was shown that there is a relationship between coal particle size and spray effectiveness, with spray knockdown efficiency increasing with increasing diameter of FCD [15]. This finding was used to select spray type and operating pressure for the development of a water curtain that can be mounted along a longwall, downwind of the shearer, to reduce the concentrations of airborne FCD, thus reducing the rate of FCD accumulations in the return. The current study uses real-time measurements to evaluate the knockdown efficiency (KE) of a water curtain in a simulated longwall environment. The spray interval and cross-directional spans of the curtain were varied to identify the effect on KE with respect to water consumption.

2. Methods

Tests to determine the KE of the spray bar were conducted at a full-scale longwall test facility at the Pittsburgh Mining Research Division, NIOSH (Fig. 1). The simulated face is 38.1 m long and 2.29 m high from floor to roof. Nineteen mock 2.0-m longwall shields cover the length of the longwall face, with a panline spanning from shield 9 to the return. Brattice curtain was hung from the shields, spanning from shield 11 to the return, creating a tunnel 1.6 m high by 3.0 m wide (Fig. 1). The ventilation of the tunnel was set to 3.5 m/s.

Float dust was introduced to the test section at the center of shield 9. The release point was directed such that dust was ejected halfway between the face and the panline, 0.51 m from the under-side of the shields. Dust was generated by using a screw-type feeder system with coal dust funneled into an eductor that used compressed air to carry the dust through hoses to the release point in the gallery. The dust supplied to the feeder (mean of 23.02 μm and standard deviation of 18.22 μm) was custom-milled to contain float-dust-sized particles. The screw feeder was adjusted until dust was provided to the gallery at an approximate rate of (50 ± 2) g per min. The dust concentration and distribution (Fig. 2) for this study were similar to the levels observed in the field [16–18].

The water curtain tested in this study was constructed from three manifolds (Repair King, Shinnston, WV), each capable of holding a maximum of seven sprays spaced 0.15 m apart. Full cone sprays (SpiralJet Nozzle No. 1/4GG3, Spraying Systems Co., Wheaton, IL) were selected for use in this study because they provided maximum knockdown during single spray tests and also have no preferential orientation [14,15]. The operating pressure of the spray bar was maintained at 1103 kPa, which consumes approximately 3.8 lpm. The water system for the NIOSH longwall gallery is a closed system that collects the water from inside the gallery, processes out the coal dust, and then returns clean water to a storage tank for future testing. The pH of the cleaned water in the storage tank is typically around 6.9. Two sets of tests were conducted to first evaluate KE for varying spray intervals and then to evaluate KE for varying the cross-directional span of the spray curtain (Table 1).

Located in the return, 7.9 m downwind of the tailgate was the XY Planar Motion System. The system consists of two 2-m linear actuators (Tolomatic, Hamel, MN), each with a 1.3-m stroke with one actuator positioned horizontally with a sled carrying the second actuator mounted vertically to a length of 80–20 slotted aluminum framing. The instrumentation in this study was mounted to a sled on the vertical actuator. Both sleds were driven by NEMA 34 high-torque stepper motors (Applied Motion, Watsonville, CA) capable of achieving a 20,000 micro-step resolution and controlled using STAC6 stepper drives (Applied Motion Products, Watsonville, CA) using serial commands. A 10:1 ratio gear box was installed between each drive motor and actuator. A custom LabVIEW virtual instrument (VI) was created to automate the motion, allowing precise and repeatable positioning of the monitoring instruments (LabVIEW software, National Instruments). The VI outputs the timestamped location of the system for parsing the data recorded by the measurement instruments.

Three instruments were used in this study. Respirable dust measurements were collected using the Personal Dust Monitor PDM3600 (Thermo-Fisher Scientific, Waltham, MA). Float dust measurements were taken using the continuous float dust monitor (CFDM). The CFDM allows a regular PDM3600 to measure total dust by bypassing the cyclone responsible for separating out the respirable fraction of dust. It consists of a housing with an isokinetic nozzle for the tapered element oscillating microbalance (TEOM) module of a regular PDM and an insert into the TEOM chamber on the PDM3600 for connecting the electronic and airflow controls. The Cloud Aerosol Spectrometer with Polarization, CAS-POL (Droplet Measurement Technologies, Boulder, CO) is part of the Cloud, Aerosol, and Precipitation Spectrometer (CAPS), which is designed for in-situ atmospheric aerosol sampling and is capable of measuring real-time size distributions of atmospheric aerosols through forward light scattering [19]. The CAS-POL has been calibrated for use with coal dust and used previously by NIOSH to determine the knockdown efficiencies of water sprays on coal dust [15,20,21]. The CAS-POL was used in this study to examine the effect of water curtain configurations on the water droplet profiles. Face concentration measurements were taken at shield 5 using one PDM3600 and one CFDM. Return concentrations were measured using one PDM3600 and two CFDMs placed on the CAS-POL wing. Each sampling phase lasted 25 min, with the instruments traversing the space and stopping at each measurement location for 5 min (Fig. 1a). The KE of the control was calculated by comparing the return dust concentrations before and after the control was activated. The CFDM records the mass of dust accumulated on the filter every minute. Using the flow rate information from the PDM calibration, a minute-by-minute dust concentration can be calculated. By matching timestamps between the LabVIEW VI positioning data and the concentration data, average concentrations were calculated for two phases: control off (dust only - no water curtain) and control on (dust and water curtain). The KE was calculated from the average concentrations measured during each phase using the following equation.

$$\mathrm{KE} = \left(\frac{\text{Concentration}_{\text{OFF}} - \text{Concentration}_{\text{ON}}}{\text{Concentration}_{\text{OFF}}}\right) * 100 \quad (1)$$

Each test condition was repeated three times. Statistical analysis of the results was performed using SAS 9.4 (SAS Institute Inc. Cary, NC) and a p-value of 0.05 was used as the threshold of significance.

3. Results

3.1. Spray interval

The average performance of the water curtain for different intervals between sprays for both total and respirable dust are shown in Fig. 3. The 21-spray configuration had the highest knockdown efficiency (KE) for both float and respirable dust fractions and was significantly different ($p < 0.05$) from the 6-, 5c-, 5w-, and 3-spray configurations for total dust and significantly different from all configurations except 18 sprays for respirable dust. The widest interval between spray configurations featured a single spray in the center of each manifold, which had the lowest KE for both total and respirable dust. When water consumption was taken into account, the configurations with 5 sprays spaced closely (5c) had the highest total dust KE but were only significantly different from the 21 and 18 spray configurations.

3.2. Cross-directional span

The average performance of the water curtain for different intervals between sprays for both float and respirable dust are shown in Fig. 4. The 21-spray configuration had the highest KE for both float and respirable dust fractions but was only significantly different ($p < 0.05$) from the narrowest (3-spray) configuration for float dust; there was no significant difference between any of the curtain spans for respirable dust. The narrowest configuration had the lowest KE for both float and respirable dust but had the highest KE when water consumption was taken into account. While the KE per gallon for the 3-spray configuration was significantly different from all other curtain widths for float dust, it was not significantly different from any of the other configurations for respirable dust.

3.3. Water curtain droplet profiles

The CAS-POL results examining the droplet diameters and count for a selection of the water curtain configurations are shown in Fig. 5. Curtain configurations in which sprays were operated with the minimum distance between all sprays (i.e. sprays from the cross-directional span experiments) are identified as solid configurations for this section. Curtain configurations that feature a non-operational spray between operational sprays are identified as spaced configurations for this section. On average, the droplets produced by the solid configurations were 32% larger than the spaced configurations. There was not a strong trend observed between the number of sprays and the particle size for either the solid or spaced configurations. The solid configurations produced a higher particle count than their spaced counterparts. In general, the number of particles decreased with decreasing spray count for both configurations, except for the 21-spray configuration.

4. Discussion

The aim of the first set of experiments in this study was to determine the effect of spray interval on the performance of a water curtain to be used on a longwall section to reduce FCD accumulations in the return. It was found that, as spray spacing increased, the KE of the water curtain decreased in a linear fashion for both float and respirable dust fractions. When water consumption was taken into account, the spray curtain performance increased with increased spacing until the spacing exceeded 0.61 m between sprays for float dust, after which it began to decrease. For the respirable dust, the fraction of KE per gallon of water stayed relatively constant until spray spacing exceeded 0.69 m, at which point it also began to decrease.

An unanticipated result was that, while there was a general trend of decreasing KE with decreasing curtain width, the only significant differences were between the 21-spray and 3-spray configurations. The spray spacing was chosen as the first series of tests because it was expected that the dust-laden air could migrate around the sprays if the space was not well covered by the curtain. Previous research has shown that sprays are effective at moving air, but sometimes this movement is not beneficial to the dust control [22]. However, these results indicate that the spray curtain does not cause significant dust migration, therefore concentrating the sprays in areas of high dust concentrations increases the KE per unit of water consumed.

The sprays used to create the water curtain in this study were selected based on previous research characterizing single spray performance. A spray characterization study using the same model of full cone spray operating at 1103 kPa found it produced droplets with a Sauter mean diameter ranging between 95 and 125 μm with droplet velocities ranging from 4 to 15 m/s [23]. It is important to note that the marked difference in measured droplet diameters between this earlier study and the current study is most likely due to the location where the measurements occurred. In the spray characterization study, the droplet diameter was measured 30.48 and 60.96 cm perpendicular to the nozzle flow centerline. In this study, the droplet measurements were taken far downwind of the curtain to characterize how much water remained airborne downwind of the curtain. Larger droplets produced by the spray are more likely to interact with the airborne dust, resulting it dropping out of the ventilating air [24,25]. It is also expected that larger droplets will naturally settle out of the ventilating air at a faster rate than the smaller droplets [26]. The spray characterization study also measured an unconfined spray dust capture efficiency on respirable coal dust of approximately 21%. A later study found the same full cone spray achieved a 40% KE for FCD when operating in an unconfined space at 1103 kPa [14]. The full cone spray achieved the highest KE of all sprays tested and does not have a preferential orientation, which is why it was selected for use in the water curtain. An unexpected finding from the spray characterization results in this study was that the 21-spray configuration produced fewer droplets than the 18-spray configuration. While the difference was moderate (approximately 24% less), this may have been due to the interactions between the sprays and airflow patterns that exist in the PMRD gallery. It was observed that, under the 21-spray configuration, a large unstable vortex formed in the spray curtain near the shield legs. This area of mixing could have potentially led to increased collisions by water droplets within the turbulent vortex causing them to drop out [26,27]. As sprays were removed from the walkway, such as in the 18-spray configuration, the vortex in the curtain became less prominent, eventually disappearing as more sprays were removed.

The results of this study demonstrated that a spray curtain can be effective at removing FCD and, to a lesser extent, respirable dust. Additionally, these results showed that understanding the distribution of dust in the area to be scrubbed can lead to a more efficient use of water by placing sprays where dust is the densest. Using the information in this study, future work will focus on understanding the interactions of multiple spray bars placed in series down the longwall face on the accumulation of float coal dust in the return.

5. 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 company names or products does not constitute endorsement by NIOSH.

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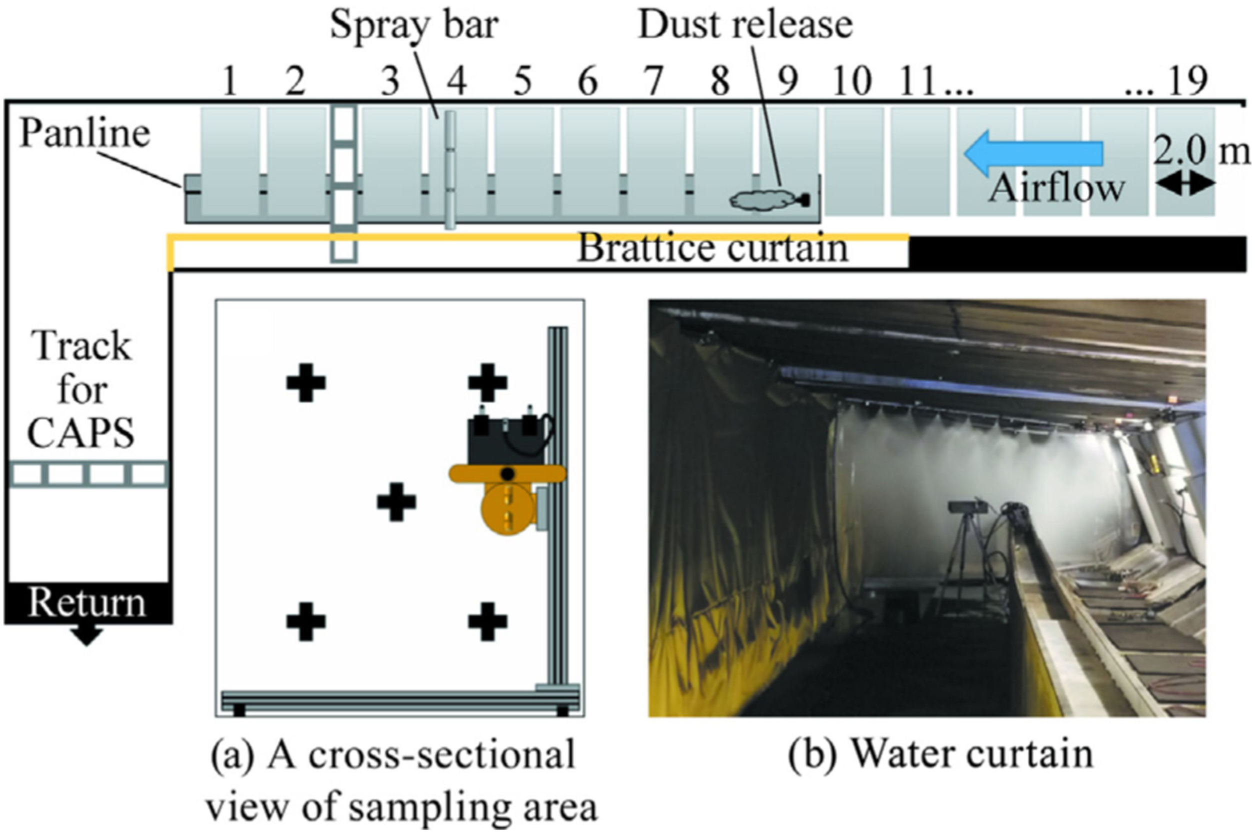


(a) A cross-sectional view of sampling area

(b) Water curtain

Fig. 1.

A schematic of the NIOSH longwall gallery, a cross-sectional view of the sampling area in the return with the plus marks indicating the locations where readings were taken during the test, and a photo of the water curtain operating the gallery.

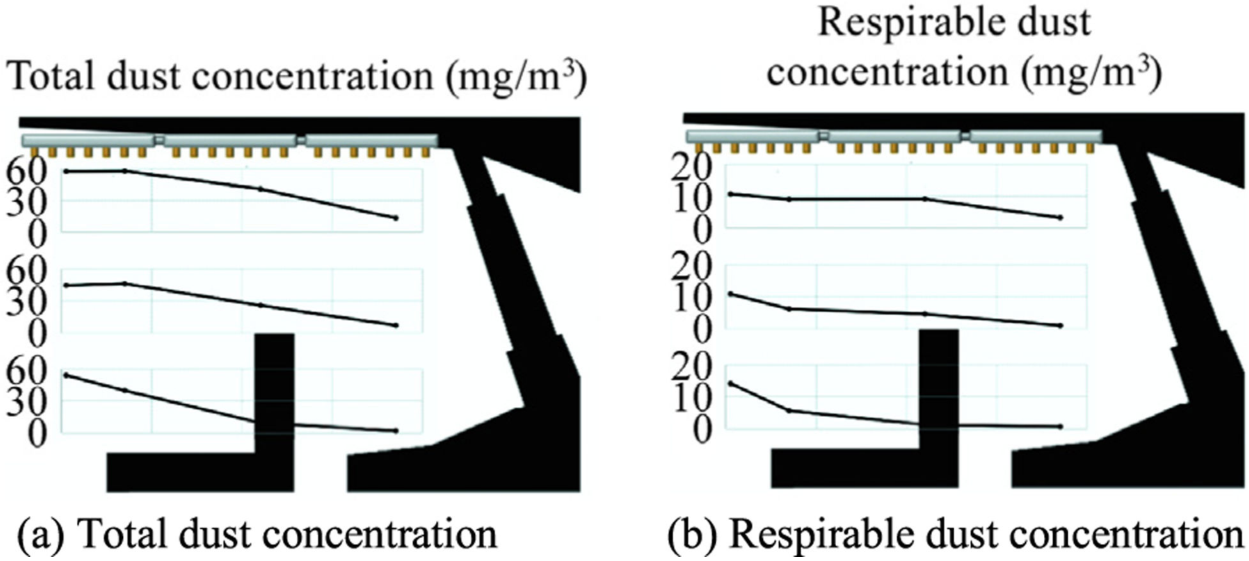
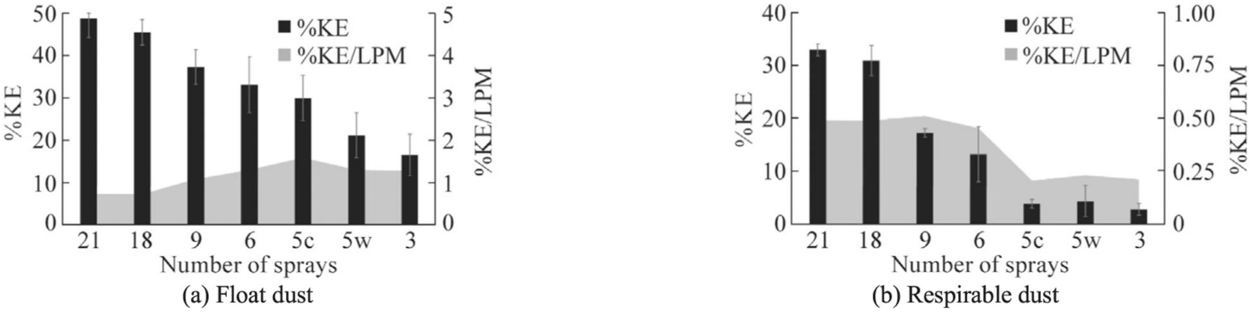


Fig. 2.

Graphs of the total and respirable dust concentrations across the gallery face between shields 2 and 3 at three different heights.



(a) Float dust

(b) Respirable dust

Fig. 3.

Average spray curtain performance for float dust and respirable dust for varying intervals of sprays.

(a) Float dust

(b) Respirable dust

Fig. 4.

Average spray curtain performance for float dust and respirable dust for different cross-directional widths.

(a) Droplet diameter

(b) Particle count

Fig. 5.

Water curtain droplet profiles.

Table 1

Spray configurations tested in the study.

Test	Number of Sprays	Average Water Consumption (L/min)	Face		Spray Configuration (Shaded = On)																	Gob	
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Varied spray interval	21	66.8	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	18	63.2	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■			
	9	34.4	■		■		■		■		■		■		■		■		■				
	6	22.9			■			■			■			■			■			■			
	5c*	19.0			■			■			■			■			■						
	5w*	18.9			■				■				■				■				■		
	3	13.3				■							■							■			
Varied cross-directionalspan	21	66.8	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	18	63.2	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■			
	15	43.6	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■						
	12	37.1	■	■	■	■	■	■	■	■	■	■	■	■									
	9	32.5	■	■	■	■	■	■	■	■	■												
	6	19.6	■	■	■	■	■	■															
	3	10.2	■	■	■																		

[*] The "c" designation represents 5 sprays spaced closely (two off between operating sprays) compared to a wider spacing for a "w" designation (three off sprays between each operating spray).