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Open-air sprays for capturing and controlling airborne float coal dust on longwall faces

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Abstract

Float dust deposits in coal mine return airways pose a risk in the event of a methane ignition. Controlling airborne dust prior to deposition in the return would make current rock dusting practices more effective and reduce the risk of coal-dust-fueled explosions. The goal of this U.S. National Institute for Occupational Safety and Health study is to determine the potential of open-air water sprays to reduce concentrations of airborne float coal dust, smaller than 75 μm in diameter, in longwall face airstreams. This study evaluated unconfined water sprays in a featureless tunnel ventilated at a typical longwall face velocity of 3.6 m/s (700 fpm). Experiments were conducted for two nozzle orientations and two water pressures for hollow cone, full cone, flat fan, air atomizing and hydraulic atomizing spray nozzles. Gravimetric samples show that airborne float dust removal efficiencies averaged 19.6 percent for all sprays under all conditions. The results indicate that the preferred spray nozzle should be operated at high fluid pressures to produce smaller droplets and move more air. These findings agree with past respirable dust control research, providing guidance on spray selection and spray array design in ongoing efforts to control airborne float dust over the entire longwall ventilated opening.

Introduction

Coal mining processes produce airborne dust that naturally deposits on the floor, roof and ribs of mine airways. These fine dust particles, termed float coal dust when smaller than 75 μm in diameter, are deposited in the return entries of coal mines and can be re-entrained by pressure waves induced by methane-air explosions (Rice et al., 1911; Nagy, 1981; U.S. National Institute for Occupational Safety and Health (NIOSH), 2006). These particles are also those most likely to participate in coal-dust-fueled explosions, which can potentiate and propagate explosions resulting in extensive damage. In order to meet compliance requirements of at least 80 percent incombustible content in the composition of material deposited in mine entries (U.S. Mine Safety and Health Administration (MSHA), 2016), coal mines apply an inerting agent, specifically, rock dust (Harris et al., 2009). Should

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methane be present in the mine atmosphere, the required fraction of incombustible content is further increased by 0.4 percent for each 0.1 percent methane. The removal of airborne float coal dust (AFCD) prior to deposition is an approach intended to make current rock dusting practices more effective by increasing the proportion of inert material to combustible material, resulting in a lower risk of coal-dust-fueled explosions.

The objective of the present research is to investigate the use of open-air water sprays to remove AFCD from a ventilating air stream. The term open-air, as used in this paper, describes an unconfined spray nozzle operating in free space, unbounded by any enclosure such as a tube, venturi or shroud. Water sprays are both effective and widely accepted as a method for controlling underground coal mine dust. In fact, water sprays are considered to be the most economical and technically feasible means of reducing dust concentrations in underground coal mines (Courtney and Cheng, 1977; Barker and Humphreys, 1996). Sprays are used in several ways to control dust in mining processes, including inhibiting dust formation, immobilizing dust to prevent it from becoming airborne, and capturing airborne dust (Cheng, 1973). Reductions in airborne dust concentrations have frequently been attributed to inertial impaction between water droplets and dust particles, forming larger agglomerates that quickly precipitate out of the airstream (McPherson, 1993). Inertial impaction activity is generally accepted as the major capture mechanism for airborne particles larger than 0.5 μm in diameter. It is this mechanism that is evaluated in this study.

Much of the previous research on water sprays in mining focused on the control and capture of respirable dust. With a median diameter of about 4 μm , respirable dust is much smaller than AFCD, which has a top diameter of 75 μm (American Conference of Governmental Industrial Hygienists, 2016). Tomb, Emmerling and Kellner (1972) attempted to parameterize the behavior of water sprays and their respirable dust capture capabilities in a ventilated tunnel. At an air speed of 0.5 m/s (100 fpm), the nozzle characteristics found to define the performance of a particular spray installation were nozzle selection, operating pressure, water flow rate, droplet velocity and mean droplet diameter. Capture efficiencies improved with increased pressures, water flow rates and droplet velocities, and diminished with larger droplet diameters. These relationships have since been confirmed by several researchers (Cheng, 1973; Courtney and Cheng, 1977; Courtney et al., 1980; Ruggieri et al., 1983; Shroeder, Babbitt and Muldoon, 1986).

Previous open-air water spray studies have further investigated differences between hollow cone, full cone, flat fan and air atomizing spray nozzle designs. When tested in an enclosed volume, air atomized and hollow cone nozzles were found to remove more respirable coal dust per unit volume of water than full cone and flat fan nozzles (U.S. Bureau of Mines, 1982; McCoy et al., 1985). Increasing pressures universally improved dust removal, which the researchers credited to increased droplet velocity and reduced droplet size.

While high-pressure sprays produce smaller droplets with higher velocities, high water pressure has been shown to potentially diminish dust capture when applied to unconfined dust clouds encountered in many mining environments. Shroeder, Babbitt and Muldoon (1986) found that as pressures increased above 689 kPa (100 psi), dust capture per unit volume of water diminished. Jayaraman, Schroeder and Kissell (1985) attributed this effect

to the inducement of localized air turbulence that moved the dust cloud rather than diluting it or increasing the rate of particle/water collisions.

Additional spray factors have been investigated for their impacts on respirable coal dust control. For example, Kost, duBreuil and Saltsman (1979) found that, independent of spray type selected, sprays oriented downstream in a 0.5-m/s (100-fpm) tunnel were 20 to 30 percent more effective at controlling airborne dust than those oriented upstream. More recent investigations by NIOSH examined spray airflow inducement and its effect on respirable dust capture potential (Pollock and Organiscak, 2007). This effort found that open-air, or unconfined, sprays with high airflow inducement did not necessarily result in higher rates of airborne dust capture, though higher pressures globally produced higher droplet velocities and improved capture efficiencies.

While much is known about spray selection and properties as they relate to respirable dust capture, these relationships must be confirmed when applied to AFCD control. The present study evaluates the ability of single open-air sprays to reduce AFCD concentrations in a controlled, high-velocity ventilated opening. By varying the spray configuration, such as spray type, orientation and pressure, the optimal configuration may be identified to successfully deploy sprays in full-scale longwall applications. Additionally, relationships between dust capture and spray characteristics and configurations are investigated to determine if prior respirable dust results may be applied to airborne capture of AFCD. NIOSH intends to use these findings to develop a series of sprays to be installed near the tailgate of the longwall face to effectively reduce AFCD concentrations over the entire opening cross-section and reduce the deposition of float dust in the return airway. The benefits of this approach are that these systems can work within the existing water supply infrastructure and could work independently of current respirable dust-focused water spray systems.

Methods

Sprays tested

The sprays used in underground installations cover a wide range of designs and capabilities. For these tests, five types of sprays were investigated: (1) single fluid hollow cone, (2) single fluid full cone, (3) single fluid flat fan, (4) single fluid hydraulic atomizing, and (5) twin fluid air atomizing. A total of seven sprays (Spraying Systems, Wheaton, IL) were tested, with two each of the hollow cone and flat fan varieties. Wide and narrow spray patterns were selected for these two spray types to evaluate the possible effect of changes in spray angle on AFCD removal.

Figure 1 shows a schematic of the types of spray nozzles tested. Six of the included sprays had been tested previously by Pollock and Organiscak (2007) for respirable dust capture efficiency, airflow inducement and various spray droplet characteristics. Gemci et al. (2003) had measured the water droplet Sauter mean diameter (SMD) and mean velocity, V , for these same sprays using a Phase Doppler Particle Analyzer at two distances along the nozzle axis under the same operating parameters.

Table 1 summarizes the spray performance values measured during these investigations. Although not evaluated previously, a hydraulic atomizing spray has been added to this current study because it is considered more technically feasible than air atomizing sprays for in-mine installation. The average fluid consumption for the conventional hydraulic sprays was 3.1 L/min (0.82 gpm) at 552 kPa (80 psi) and 4 L/min (1.06 gpm) at 1,103 kPa (160 psi). Spray angles ranged from 21 to 88 degrees.

Dust tunnel configuration

Tests to evaluate the dust capture ability of seven open-air sprays were conducted at the NIOSH Mining Program facility in Pittsburgh, PA. The existing NIOSH full-scale longwall dust gallery was modified to route air through a featureless, nearly rectangular opening with height of 1.6 m (5.4 ft), width of 0.9 m (3.0 ft) and length of 19.0 m (62.5 ft). Each water spray was individually placed on the top surface, 7.3 m (24.0 ft) from the tunnel entrance on the centerline of the tunnel. This relative location is depicted in the schematic diagram in Fig. 2. Depending on the orientation tested, the sprays were angled at 45 degrees from horizontal along the length of the tunnel in either the upstream or downstream direction. Airflow through the tunnel was induced by a series of three centrifugal fans located on the exhaust side and controlled by adjustment of regulators to maintain a velocity of 3.6 m/s (700 fpm).

The establishment of an experimental AFCD concentration in the tunnel was achieved by continuous material release through a laboratory dust dispersion system. A vibrating screw feeder located outside of the tunnel supplied dust to a compressed air-powered venturi eductor connected to a length of rubber hose with internal diameter of 19 mm (0.7 in.). A fixed release point 0.5 m (1.5 ft) from the roof and 17.8 m (58.5 ft) upwind from the dust sampling location was established on the centerline of the tunnel interior, and alignment in the downwind direction was confirmed before each test. Dust was introduced at a rate of 50 g/min (6.6 lb/h) \pm 4 percent with verification before and after each test segment. The feed material was coal dust from the Pocahontas 3 coal seam in West Virginia (Penn Keystone Coal Co., Claysburg, PA) that had been custom-ground and screened by Hadsell Chemical Processing (Waverly, OH) to a size of 100 percent smaller than 200-mesh, or 74 μ m. The resulting dust had a volume mean diameter of 23.02 μ m and median diameter of 20.47 μ m, with 29 percent smaller than 10 μ m.

Dust sampling

Dust concentrations were measured at the tunnel exit using gravimetric sampling techniques for AFCD. The development and evaluation of the AFCD sampler, which is based on the Institute of Occupational Medicine (IOM) sampler for inhalable dust, is described in Barone et al. (2016) and Janisko et al. (2015). The AFCD samplers used in this study (Fig. 3) were fitted with the appropriate isokinetic nozzles to approximately match the tunnel airspeed when the sampler was operated at 2 L/min. In this case, a 3.06-mm (0.12-in.) internal diameter nozzle directed upstream provided an inlet flow velocity of 4.6 m/s (899 fpm). During operation, dust-laden air was pulled through the isokinetic nozzle and a custom inlet adapter to be deposited on the surface of a preweighed, open-faced IOM glass fiber filter

(SKC Inc., Eighty Four, PA). Dust caps were placed on the isokinetic nozzles to prevent deposition of dust during nonsampling periods.

Prior to each sampling period, a stabilized AFCD concentration was established. Upon the start of sampling, the dust caps were removed and a vacuum pump began drawing air at a rate of 2 L/min through each sampler. Airflow through each sampling assembly was maintained using critical orifices calibrated to 2 L/min \pm 4 percent.

While operating continuously, three AFCD sampling units were moved across the entire tunnel opening by a planar motion assembly. Fifteen areas — three across and five down — were selected based on EPA Method 1, for stationary samples of 1 min each. After 1 min, the sampler was moved to the centerpoint of the next region, until samples were collected for all 15 locations. These sampling points are illustrated in Fig. 4. The entire sampling sequence was 17 min in duration, including time to move between each stationary point. Each test consisted of three sampling sequences: (1) dust only, (2) water spray only and (3) dust with water spray. Unique gravimetric filters were used for each sampling sequence. Following each test, filters were desiccated and placed in the environmentally controlled weighing laboratory at the NIOSH facility for 24 hours of conditioning. Weight gain for each filter and resulting dust concentration were determined by post-weighing.

Data analysis

Gravimetric dust concentrations were determined by dividing the accumulated mass by the total volume of air sampled. The concentrations measured by each sampler were averaged together to ascertain the dust concentration for each phase of the spray configuration test. Dust capture efficiencies were further calculated by dividing the difference in dust concentrations for the water and dust phase by the baseline dust-only concentration for each test: $E = (C_0 - C)/C_0$, where C_0 is the initial concentration of AFCD and C is the concentration of AFCD after treatment by water spray. The sprays were operated at either 552 kPa (80 psi) or 1,103 kPa (160 psi) for single-fluid sprays and 172 kPa (25 psi) or 345 kPa (50 psi) for the twin-fluid spray. Sprays were oriented in either the upstream or downstream direction, angled 45 degrees down from the top surface. To measure the dust capture efficiency for the chosen test conditions, a randomized full factorial experimental design was adopted, with three replicates for each test condition. Data were evaluated using SPSS Statistics Version 19.0 (IBM, Armonk, NY). The level of significance used for all statistical tests was 0.05, 95 percent confidence interval, unless otherwise stated.

Results

Eighty-four tests were performed to measure the dust capture efficiency of seven different spray nozzles. The AFCD capture efficiencies for each spray, level of pressure, and nozzle orientation are shown in Fig. 5. The average AFCD capture efficiency for all sprays for all conditions was 19.6 percent. The full cone spray, FC59, exhibited the highest overall efficiency, 26.4 percent, across all conditions as well as the highest efficiency for any pressure and orientation combination: high pressure, upstream orientation, 40.1 percent. The wide-angled nozzles of both the hollow cone, HC81, and flat fan, FF50, varieties had similarly high overall capture efficiencies of 24.8 and 22.6 percent, respectively. The air

atomizing spray, AA21, was the least efficient, 12.8 percent, at high pressure, and the third least efficient, 8.3 percent, at low pressure, resulting in an overall lowest average performance of 13.4 percent capture efficiency. Higher pressures resulted in higher capture efficiencies in almost all situations. This can be seen for all cases except the air atomizing spray in Fig. 5, with the line for average high-pressure AFCD capture efficiency remaining above the line corresponding to average low-pressure capture efficiency.

Three-way factorial analysis of variance, or ANOVA, was conducted to compare the main effects of spray choice, pressure and orientation, and the interaction effects between spray choice, pressure and orientation on the observed AFCD capture efficiencies. The main effect for spray choice yielded an F ratio of 6.893, $p = 0.000$, indicating a significant difference in capture efficiency between spray types. The main effect for pressure produced a significant difference in capture efficiency, $F = 57.189$, $p = 0.000$, with higher pressures, leading to improved AFCD capture. Orientation was not statistically significant, $F = 2.718$, $p = 0.105$. There was a significant two-way interaction of spray type and pressure, $F = 5.009$, $p = 0.000$, revealing that certain sprays were more effective when operated at high pressure than other sprays. A second significant two-way interaction was observed between spray type and orientation, $F = 3.168$, $p = 0.010$, indicating that certain sprays better removed AFCD from the airstream when operated in a particular direction.

A post-hoc Tukey honest significant difference, or HSD, test on the main effect for spray choice identified significant differences between FC59 and AA21, with $F = 12.99$, $p = 0.007$; FC59 and HC33, with $F = 10.58$, $p = 0.050$; and HC81 and AA21, with $F = 11.43$, $p = 0.026$. These results suggest that spray choice, especially among the selected single-fluid sprays, may have little influence when attempting to remove airborne dust from a ventilation airstream. Other considerations in terms of spray geometry, coverage or system capacity may be more important to the effective implementation of unconfined sprays in practice.

Regression analysis was conducted on the experimental capture efficiency to determine possible significant pressure and orientation relationships for each spray. The influence of pressure and orientation was modeled for each spray nozzle type using stepwise linear regression with indicator variables (Olsson, 2002). The AFCD capture efficiency model took the form of the first-order linear response function:

$$y_i = \beta_0 + \beta_1 \chi_{1i} + \beta_2 \chi_{2i} + e_i$$

where y_i = regression model dust capture efficiency estimate; β_0 = model constant; β_1 = pressure coefficient; β_2 = orientation coefficient; $\chi_1 = 0$ if low pressure and 1 if high pressure; $\chi_2 = 0$ if oriented downstream and 1 if oriented upstream; and e_i = error term.

The calculated regression terms for each spray nozzle are listed in Table 2. AFCD capture efficiency could be accurately predicted for five of the tested sprays by including level of pressure and/or spray orientation. Only the model for the hydraulic atomizing spray nozzle, HA88, included both pressure and orientation terms at a 0.05 level of significance. The negative coefficient for this nozzle's orientation indicates that the predicted capture efficiency is lower when oriented into the airflow. Prediction models for four of the sprays

included positive terms for pressure, indicating that increases in pressure resulted in improved capture efficiency. This trend is seen graphically in Fig. 5 for all sprays except air atomizing.

Pearson product-moment correlation coefficients were computed to assess the potential relationship between AFCD capture efficiency and spray pressure, orientation, fluid quantity, spray angle, droplet SMD, droplet velocity, induced airflow and spray power. The air atomizing spray was removed from this analysis because the droplet formation uses a twin-fluid mechanism and the performance characteristics tend to be vastly different from single-fluid hydraulic sprays. Similarly, the hydraulic atomizing spray was removed from some comparisons where characteristic data were unavailable.

The results for all correlations are presented in Table 3. There was significant positive correlation between AFCD capture efficiency and spray pressure, induced airflow and spray power. At the 0.10 level of significance, two additional correlations were identified. A negative correlation was observed between capture efficiency and droplet SMD at the 0.3-m (1-ft) distance. This relationship indicates that smaller droplets generally resulted in increased dust removal efficiency. A second correlation at the 0.10 level was found between water quantity and AFCD capture efficiency, where increases in water usage resulted in improved AFCD capture. No correlations were observed between AFCD capture efficiency and spray orientation, spray angle and droplet velocities. In general, the results suggest that sprays that are operated at higher pressure, use more water, produce smaller droplets and induce more airflow tend to remove more AFCD from the ventilation airstream.

Discussion

Many mines will be able to tolerate only a small stationary source of water on the longwall face. Therefore, when designing a full face spray installation, it will be necessary to maximize AFCD capture while minimizing water consumption. To identify the singular spray with the best capture potential at the lowest water consumption rate, the AFCD capture efficiencies measured in this study were normalized by water flow rate in liters per minute. This approach had been used in past studies to consider dust reductions per unit of water flow (McCoy et al., 1985). The capture efficiencies per spray water flow rate for the seven tested sprays are shown in Fig. 6. After making this adjustment, the hydraulic atomizing spray excelled at both low and high pressures, reducing AFCD concentrations by 10.5 and 12.6 percent per unit water, respectively. These values compare favorably with the corresponding averages for all sprays of 6.1 and 7.2 percent per unit of water.

AFCD capture efficiencies were found to improve for increases in pressure, induced airflow, spray power and water flow rate, and for decreases in droplet diameter. These spray characteristic effects agree with those established through previous respirable dust research. However, this study did not observe a significant effect related to droplet velocity or orientation. Although orientation was not found to be a significant factor in AFCD capture, it should be noted that the air speed in these trials was seven times higher than that previously tested (Kost, duBreuil and Saltsman, 1979). The preferred spray choice was also not the same as in prior closed chamber tests for respirable dust removal (U.S. Bureau of

Mines, 1982; McCoy et al., 1985). In these current tests, the full cone nozzle produced the largest reductions and the air atomized nozzle was found to remove the least amount of dust. Even when considering capture efficiency per unit volume, the air atomizing nozzle did not perform as well as the hydraulic atomizing spray. It is possible that the high-speed ventilating air disrupted the air atomizing nozzle's spray pattern and did not allow for water droplets to fully encompass the tunnel opening.

This study considered the laboratory capture of coal dust sized smaller than 75 μm in diameter. It is possible that different dust sizes and compositions found in actual underground mine environments may have an impact on the performance of these selected sprays. Additionally, based on the position of any spray system along the longwall face, larger dust particles may have deposited naturally, leaving only a smaller-sized dust fraction in the airstream.

The performance characteristics of the hydraulic atomizing spray have not been measured and were not included in the statistical investigation of significant correlations between AFCD capture efficiency and droplet diameter, droplet velocity, and induced airflow. Additionally, the air atomizing spray was not included in the correlation analysis due to its different droplet formation mechanism. It is possible that these two sprays would modify the analysis and result in the discovery or omission of additional relationships.

An important element in the success of a spray-based dust capture system would be the coverage over the ventilated opening. In this investigation, droplet coverage was not measured. It has been shown that in order for droplets to reach distant areas from their release point, spray nozzles must produce high-momentum droplets, with both large droplet diameters and high velocities (Swanson, Agasty and Langefeld, 2012). While this study found no evidence that higher velocities lead to higher capture efficiencies, larger droplets are shown to generally decrease capture potential. A final system design should strive to place the selected sprays close to the target location to improve particle interception.

The in-mine operation of these tested sprays was not investigated in this study. Water quality requirements and filtration needs to minimize plugging of the smaller-orifice nozzles must be considered in the design of functional spray systems for longwall installation. It is possible that larger-orifice spray nozzles would be required to maintain system performance, despite a potential decrease in droplet diameter and resulting capture efficiency. This may not be an effective solution because particles larger than even the largest practical nozzle orifice have been found in mine water supplies (Courtney and Cheng, 1977). Twin-fluid sprays may also not be appropriate for use underground, because an auxiliary high-pressure air source is required for their operation. The relatively low performance of the air atomizing spray in a high-velocity airstream makes this additional demand likely unnecessary to achieve adequate AFCD control.

Conclusions

Accumulations of float coal dust present a hazard in underground coal mines that must be regularly addressed through the application of inerting materials. Reductions in AFCD

concentrations would lessen the danger of combustible material deposition in return ventilation airways and improve the effectiveness of inertization efforts. One approach used in prior airborne dust control efforts has been the application of water sprays to capture a portion of the respirable dust contained in the mine atmosphere. This study evaluated the ability of these same sprays to reduce concentrations of float-dust-sized coal particles.

Gravimetric samples show that airborne float coal dust capture efficiencies averaged 19.6 percent for all sprays under all conditions, with a range of 8.3 to 40.1 percent. The full cone spray exhibited the highest average efficiency, 26.4 percent, across all conditions as well as the highest efficiency for any pressure and orientation combination: high pressure, upstream orientation, 40.1 percent. When accounting for water consumption, hydraulic atomizing sprays demonstrated the highest dust capture potential. Orientation had a significant influence for only two spray types, with increased capture efficiencies for air atomizing sprays and lower efficiencies for hydraulic atomizing sprays when directed into the airstream. Increases in spray nozzle fluid pressure increased airborne dust capture for four of the six hydraulic sprays tested. Significant positive correlations between AFCD capture efficiency and induced airflow, spray power and water consumption were observed. Airborne dust capture also increased with decreasing droplet diameter. Similar relationships were not statistically significant for mean droplet velocity or spray angle.

As many of the findings are consistent with previous respirable dust control work, these tests have demonstrated that similar dust capture principles and mechanisms may be in effect for both respirable coal dust and AFCD. It is anticipated that future AFCD efforts may use the large amount of respirable dust literature for guidance in developing functional and effective controls to reduce the burden of AFCD accumulations in the return airways of coal mine operations. Based upon the information of spray nozzle characteristics and capture performance obtained in this study, NIOSH is continuing to develop full-scale spray systems to be tested for AFCD control in longwall face environments.

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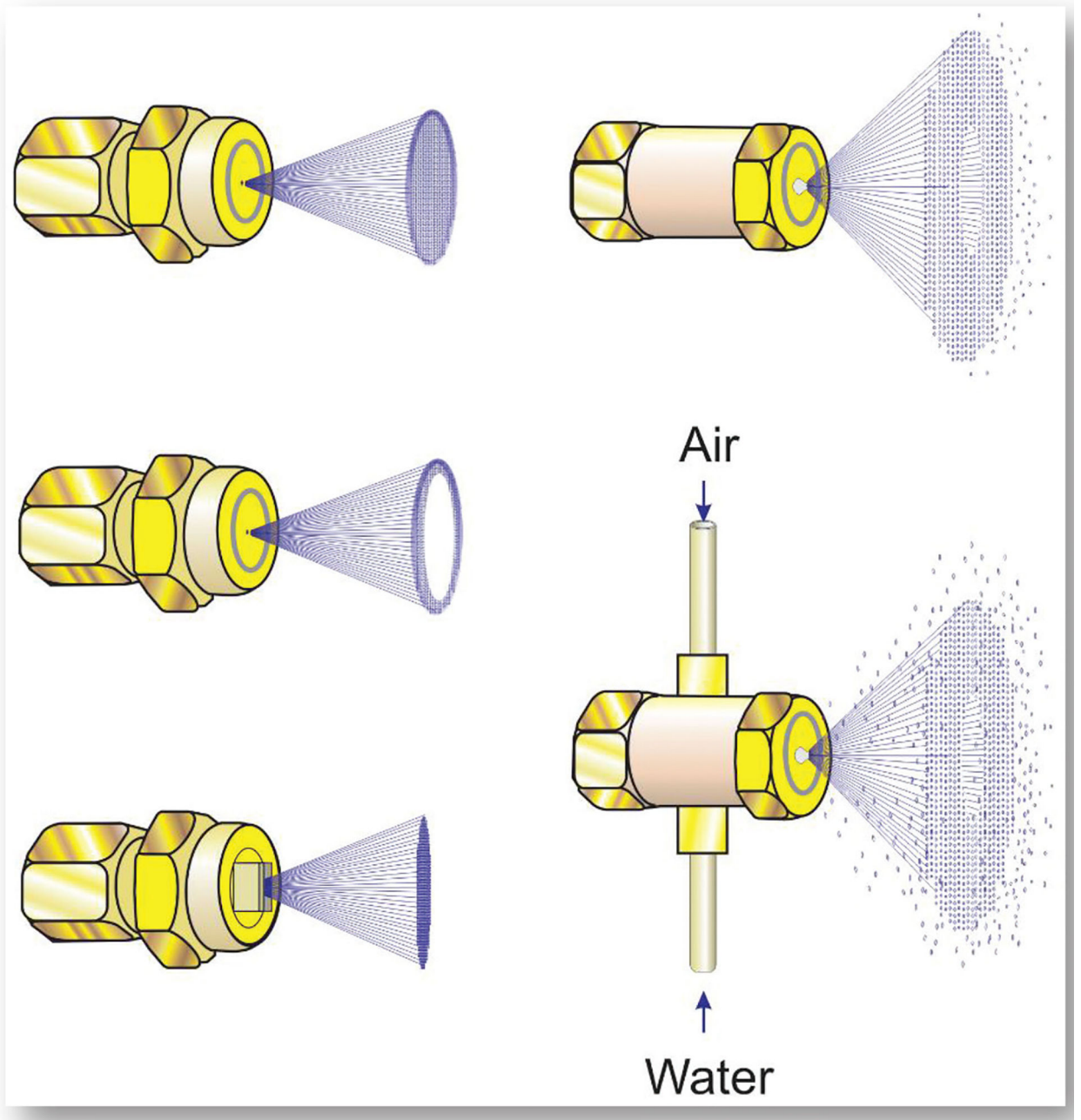


Figure 1. Spray nozzles tested. Clockwise from top left: full cone, single fluid atomizing, twin fluid atomizing, flat fan and hollow cone (Colinet et al., 2010).

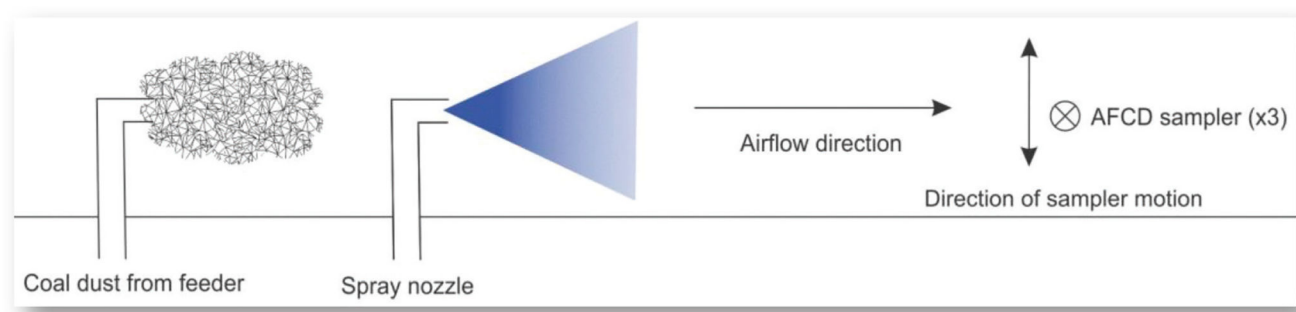


Figure 2.
Schematic diagram of tunnel, showing dust introduction, spray nozzle and sampling apparatus.



Figure 3.
NIOSH AFCD sampler adapted from IOM sampler with isokinetic nozzle (blue) and custom inlet adapter (black).

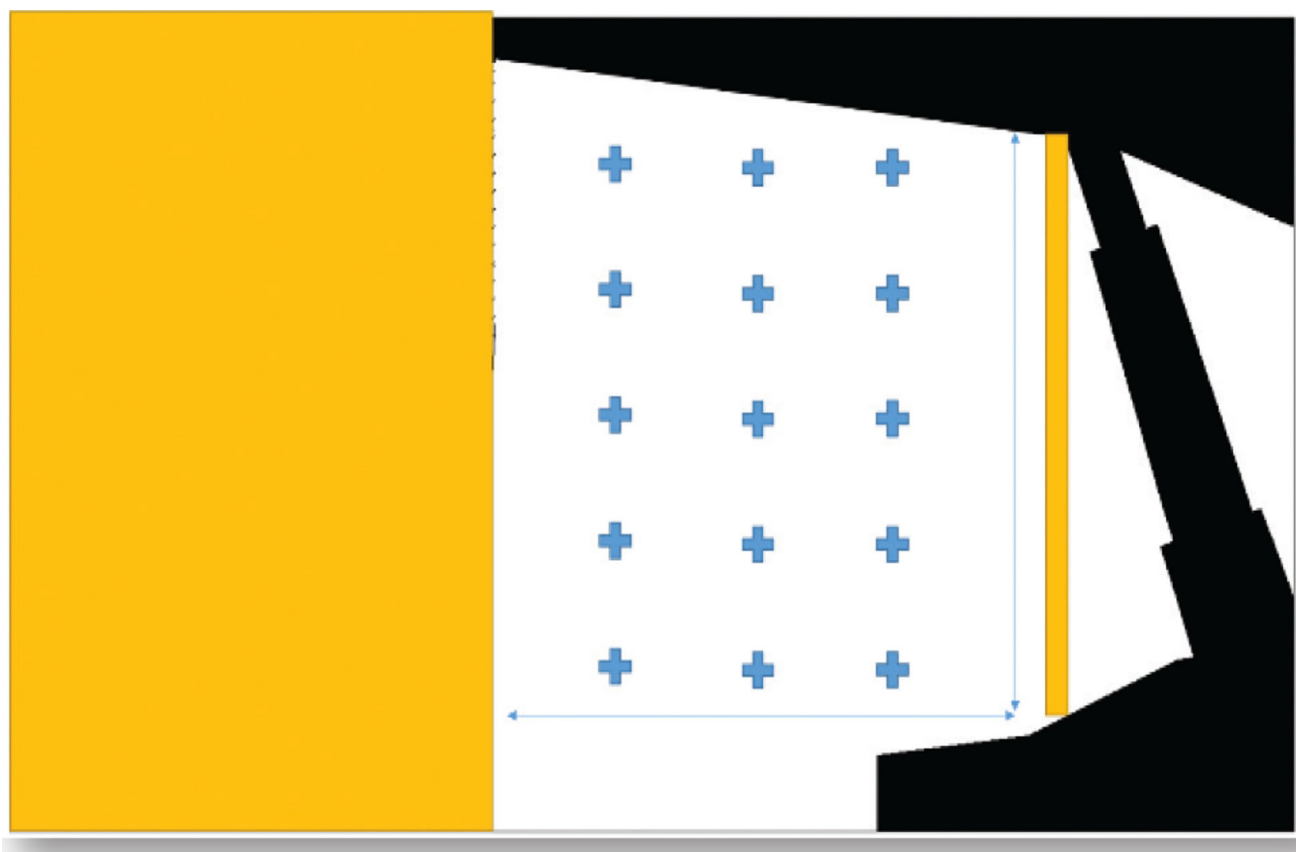


Figure 4.
Fifteen points selected for stationary sampling of airborne dust.

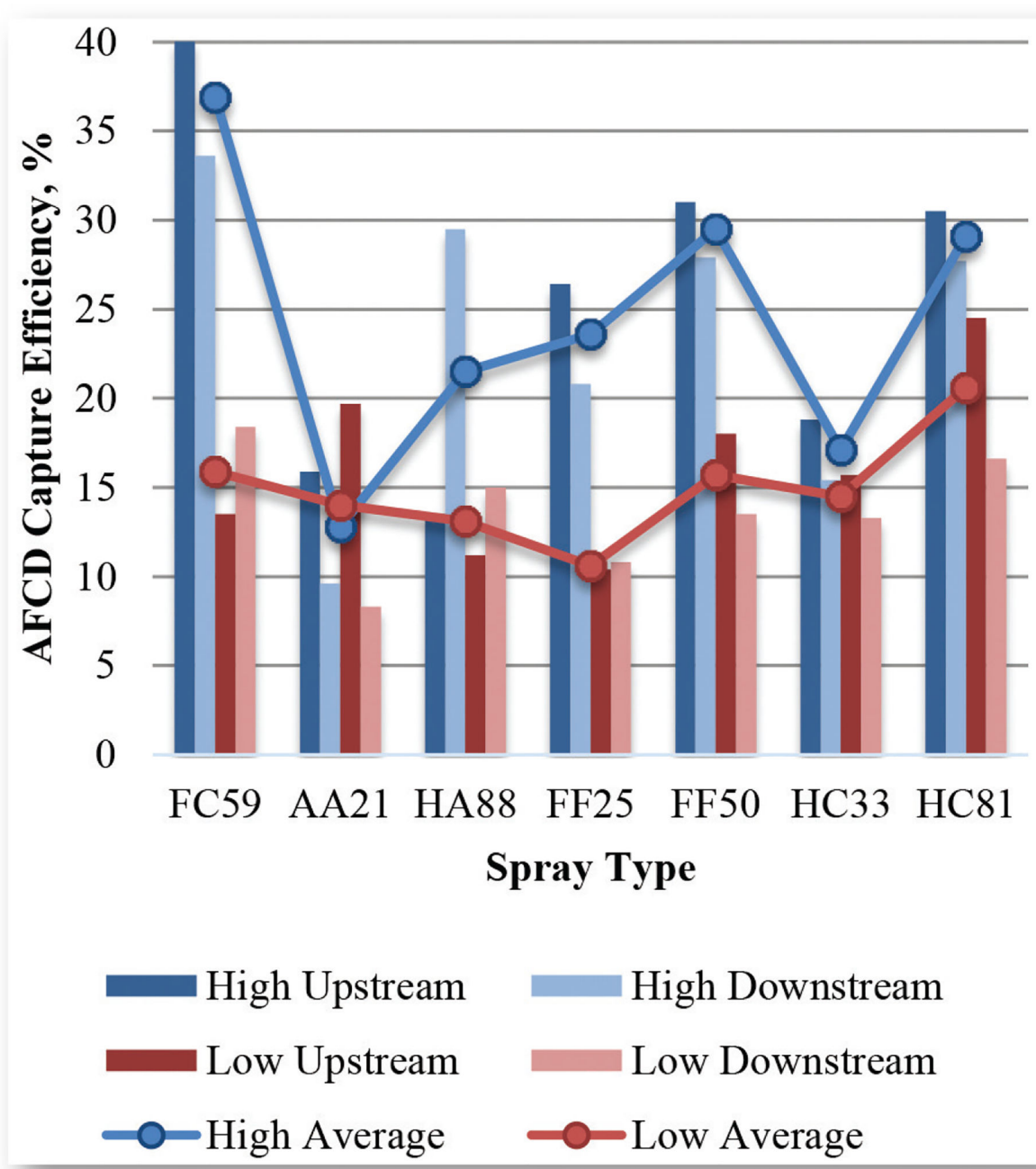


Figure 5.
AFCD capture efficiency for seven tested sprays.

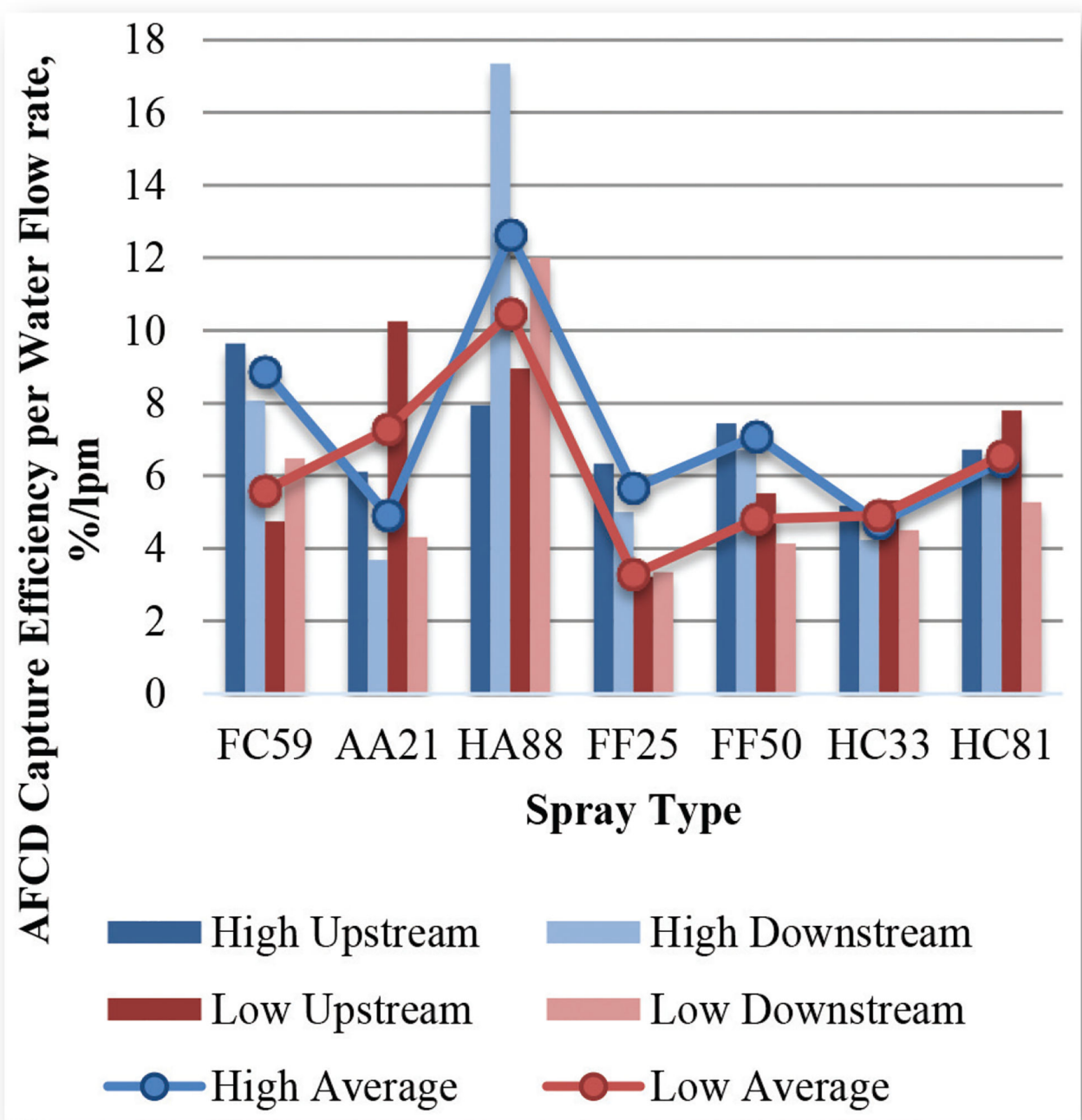


Figure 6.
AFCD capture efficiency per water flow rate for seven tested sprays.

Spray nozzles, operating parameters and spray characteristics (adapted from Pollock and Organiscak, 2007; Gemci, Chigier and Organiscak, 2003).

Table 1

Spray nozzle designation	Spray name, type	Pressure (kPa)	Water/(air) flow rates (L/min)	Angle	SMD at 0.3 m (μm)	SMD at 0.6 m (μm)	V at 0.3 m (m/s)	V at 0.6 m (m/s)	Induced airflow (m ³ /s)	Spray power (W)
FC59	Full jet nozzle GG3, single fluid full cone	552	2.84	59°	129.3	125.8	6.3	4.3	0.35	26.1
		1,103	3.63		106.1	108.5	9.7	7.8	0.51	66.8
AA21	Air atomizing nozzle J-SU42, twin fluid full cone	172 air/water	1.92 (99.1)	21°	166.0	165.0	13.8	8.5	0.17	197.5
		345 air/water	2.60 (163)		143.0	146.0	22.4	12.5	0.26	520.6
HA88	Hydraulic atomizing nozzle LNN14, single fluid full cone	552	1.25	88°	–	–	–	–	–	11.5
		1,103	1.70		–	–	–	–	–	31.3
FF25	Uni jet nozzle TT2506, single fluid flat fan	552	3.22	25°	244.3	252.3	13.3	9.8	0.29	29.6
		1,103	4.16		198.4	201.2	21.2	14.4	0.39	76.6
FF50	Uni jet nozzle TT5006, single fluid flat fan	552	3.26	50°	234.6	220.8	14.7	8.8	0.46	29.9
		1,103	4.16		195.3	196.9	23.5	14.5	0.64	76.6
HC33	Uni jet nozzle TTD4, single fluid hollow cone	552	2.95	33°	138.3	109.5	8.3	4.9	0.38	27.1
		1,103	3.63		98.2	91.6	11.7	8.0	0.48	66.8
HC81	Uni jet nozzle TTD6, single fluid hollow cone	552	3.14	81°	73.8	89.1	2.6	1.3	0.76	28.9
		1,103	4.54		60.1	82.6	3.3	2.2	1.11	83.5

Table 2

Summary of stepwise regression analysis for spray parameters predicting AFCD capture efficiency (NS = not statistically significant, NA = not applicable).

Spray name	Constant	Pressure coefficient	Orientation coefficient	Adjusted R ²
FC59	15.933	20.917	NS	0.776
AA21	8.983	NS	8.833	0.570
HA88	18.067	8.367	-9.933	0.618
FF25	10.633	12.967	NS	0.489
FF50	15.717	13.767	NS	0.653
HC33	NS	NS	NS	NA
HC81	NS	NS	NS	NA

Table 3

AFCD capture efficiency and spray characteristics: Pearson correlations (numbers in bold = statistically significant at the 0.05 level, numbers in italic = statistically significant at the 0.10 level).

Correlation tested	Correlation
Efficiency and spray pressure (kPa)	0.657
Efficiency and orientation	0.218
Efficiency and fluid quantity (m ³ /s)	<i>0.402</i>
Efficiency and spray angle (°)	0.298
Efficiency and SMD (at 0.3 m, µm)	<i>-0.407</i>
Efficiency and SMD (at 0.6m, µm)	-0.340
Efficiency and velocity (at 0.3m, m/s)	-0.010
Efficiency and velocity (at 0.6m, m/s)	0.014
Efficiency and induced airflow (m ³ /s)	0.532
Efficiency and spray power (W)	0.622