Underground Ventilation – Tukkaraja (Ed)

Investigation on the effect of water pressure on spray performance for removal of respirable dust

H. Jiang, S. Klima, T. Beck & Y. Zheng
Centers for Disease Control and Prevention (CDC), National Institute for Occupational Safety and Health (NIOSH), Pittsburgh, PA, USA

ABSTRACT: Dust control challenges exist in numerous mining applications and is especially prevalent in confined production spaces like mining faces. Water sprays are the most economical and technically feasible means of reducing dust concentrations in a wide range of applications. This study investigated the respirable dust knockdown performance and submicron particle suppression behavior for a typical mining spray nozzle operating at pressures ranging from 100 to 800 psi. A confined chamber dust removal evaluation approach and an optical particle counter were used for this study. For respirable dust knockdown, high spray pressures were more effective in lowering dust concentrations. However, submicron-sized particles are difficult to remove; at 100-psi water pressure, the knockdown fraction for submicron particles remained at only 40 % at the end of a 1-hr test. The lowest suppression effective size boundary was identified from 0.465 to 0.897 μm under a tested pressure range. Resuspension of submicron material was observed at all water pressure levels after the start of the spray operation. The resuspended submicron dust remained airborne for different durations under different spray pressures. Overall, results show a low capture efficiency and a high resuspension possibility for micron- or nano-scale particles under testing conditions.

1 INTRODUCTION

Dust control problems exist in a variety of industrial sectors, from construction sites to mining sites (Stacey et al., 2011). It is even more challenging when dealing with respirable dust in a confined production space, such as the underground mining face. Mining activities can generate a large amount of dust particles including respirable dust and even submicron dusts (Sarver et al. 2019). Despite the Mine Safety and Health Administration (MSHA) setting regulations to improve coal miner health and safety, there has been a dramatic increase in the prevalence of progressive massive fibrosis among underground coal miners in central Appalachia over the past decade (Doney et al., 2019). It has long been recognized that the inhalation and deposition of respirable dust in the lung respiratory tract is the main cause for pneumoconiosis and silicosis in coal miners (Cecala et al., 2019). The human respiratory tract can be divided into three main regions—the head, tracheobronchial region, and the gas-exchange or alveolar region (Brown et al., 2013). Respirable fraction specifically means the mass fraction of inhaled particles penetrating into the gas-exchange region. In terms of particle size, the limit for entering the alveolar region is between 10 and 15 μm (WHO, 1999; European Committee for Standardization, 2014). These respirable fractions that cause the greatest hazard include quartz and other dusts containing free crystalline silica produced by grinding or drilling.

Dust mitigation techniques commonly used in the underground mining workplace generally include three distinct types: (1) ventilation systems to dilute and transport dust away from workers, (2) isolation of workers by enclosures, and (3) capture of airborne dust using water sprays. Among these techniques, water sprays are the most economical and technically feasible

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means of reducing dust concentrations in a wide range of applications (Beck et al., 2018). Several water spray applications for controlling longwall face dust have been developed and adopted in recent years. Drum-mounted, full-cone water sprays are very effective for dust suppression at the point of coal fracture and minimizing dust liberation during coal transport. Shearer-body-mounted water sprays oriented downwind can promote movement of dust-laden air along the face side of the shearer to prevent migration into the walkway. There are also water sprays mounted on the longwall shield to address the dust generated during shield movement. Underside shield canopy sprays can create a moving water curtain to contain the dust cloud near the drum area and away from the walkway (Colinet et al. 2010). The atomization characteristics and dust removal efficiency of high-pressure sprays were investigated for optimizing the performance. Cheng et al. (2011) conducted a field test showing that increasing the longwall shearer and shield spray pressure from 290 to 1,160 psi decreased the dust concentration from 536 mg/m^3 to 97 mg/m^3. This research also recommended the application of 1,160-psi spray pressure for better respirable dust capture efficiency in coal mines. An experimental study concluded that the spray pressure is directly proportional to spray water flow, while inversely proportional to the water droplet size and spray angle (Han et al., 2020). The overall dust suppression efficiency for total dust and respirable dust increased with the increase of pressure from 290 to 1,160 psi.

Dust capture by water droplets can be accomplished by numerous mechanisms including inertial impaction, interception, diffusion, thermophoresis, and electrostatic charge collection. These processes usually occur simultaneously, although inertial impaction and interception are predominant for the capture of coal-mine-generated dusts. The theoretical foundation for high-pressure suppression performance improvements can be found from the droplet breakup mode (Majithia et al., 2008), dust suppression efficiency by inertial impaction (Walton and Woolcock, 1960), and dust suppression efficiency by interception (Fuchs, 1964), illustrated in equations 1, 2, and 3 respectively:

$$D_w = \frac{\sigma We_c}{\rho_g \upsilon^2} \tag{1}$$

$$\eta_{imp} = \frac{1}{(1 + 0.7/St)^2} \tag{2}$$

$$\eta_{int} = \left(1 + D_p/D_w\right)^2 - \frac{1}{1 + D_p/D_w} \tag{3}$$

where

$$St = \frac{C_f \rho_p D_p^2 v}{9\mu D_w} \tag{4}$$

D_w is the diameter of water droplet, m; We_c is the critical Weber number when the droplet starts to breakup; ρ_g is the air density, kg/m^3; v is the relative velocity between the dust particles and the droplets, m/s; σ is the surface tension, N/m; η_{imp} is the dust suppression efficiency by inertial impaction; St is Stock number of particle; η_{int} is the dust suppression efficiency by interception; D_p is the diameter of dust particle, m; C_f denotes the Cunningham correction factor; ρ_p is the density of the dust particles, kg/m^3; μ denotes the air dynamic viscosity, Pa·s.

As the spray pressure increases, the water flow rate increases and thereby results in higher droplet velocity. According to Eq. (1) a higher relative velocity produces smaller water droplets. Eq. (2) and (4) show that a smaller water droplet and larger relative velocity can increase the dust capture efficiency by inertial impaction. Eq. (3) demonstrates that the interception efficiency for small dust particulates can be limited but reducing the size of water droplets can increase the dust interception efficiency. In summary, high-pressure spray generates finer water droplets and can yield a higher dust suppression efficiency.

There is still skepticism of the water suppression effect for respirable particulates by researchers (Organiscak and Page 2005). The detailed size-specific behavior within the respirable range under suppression was rarely studied. The spray knockdown efficiency for submicron particles was unknown for either low- or high-pressure spray in coal mining. In this study, the respirable dust suppression characteristics were investigated in a confined chamber under spray pressure that ranged from 100 to 800 psi. The spray respirable dust knockdown was monitored and evaluated over a 1-hour testing period. The suppression behavior for submicron particles under different pressures were also investigated.

2 LABORATORY EXPERIMENTAL SYSTEM AND METHODOLOGY

A confined-chamber, dust-removal evaluation approach (McCoy et al., 1985) was used to investigate the respirable dust suppression effectiveness for a water spray over the pressure range from 100 to 800 psi. The advantage of this confined-chamber approach compared with an open-ended duct approach (Han et al., 2020) is that detailed dust particle decay characterization in different size ranges can be easily monitored. In addition, dust was only introduced at the beginning of the test to reach an initial concentration instead of a constant dust source throughout the test which can create an unstable baseline.

A 512-ft^3 dust chamber (8 ft by 8 ft by 8 ft) constructed of plywood was used for testing in this study, Figure 1. Keystone Mineral Black 325 BA coal dust (Keystone Filler & Mfg. Co., Muncy, PA) was introduced through an air inductor into the chamber through a metal pipe that was grounded to eliminate the risk of imparting any static charge to the particles. A 35-ft^3/s mixing fan located at the upper corner of the chamber ensured the dust was sufficiently homogenized after injection. A WhirlJet® BDM3 hollow cone spray (Model 3/8-BDM-3, Spraying Systems, Wheaton, IL) with an orifice of 0.094 inch was mounted at a 58-inch height on the centerline axis of the chamber; the spray mechanisms provided by the manufacturer are shown in Figure 2. The water enters the nozzle body through a hole from its side, then the water spins at high speed in the whirl chamber. The high-speed rotation causes the water to exit the orifice in a hollow cone pattern. The spray geometry and mechanism are the same with the brass and stainless steel 3/8 BD3 sprays but manufactured with nylon body material.

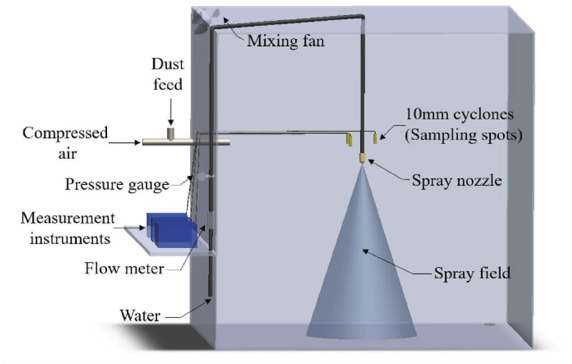


Figure 1. Dust chamber system for dust deposition and water spray dust suppression test.

This study is only interested in the respirable particles, over-sized particles in the raw coal dust were removed by cyclone during the sampling process. In this test, three real-time aerosol monitors (TSI Dust Trak$^{@}$ II aerosol monitor model 8530, Shoreview, MN) were connected to Dorr-Oliver 10-mm nylon cyclones for the purpose of measuring the respirable size fraction of dust (≤ 10 μm). Sampling points were located 10 inches above the spray. During testing, one aerosol monitor continuously sampled and recorded the dust concentration, while the other two monitors began sampling and recording when dust concentration reached the start criteria. The sampling flow rate for each monitor was set to 1.7 L/min, and the data logging interval was 5 seconds. All reported dust concentrations are the relative mass concentration measured by an aerosol monitor instrument unless expressed otherwise. One Optical Particle Sizer (OPS) (TSI model 3330, Shoreview, MN) was used to obtain the particle count results with a sampling rate of 1 L/min. The OPS operates on the principle of single particle counting. Particle pulses are counted individually and binned into the 16 channels based on their pulse heights. Sixteen (16) bin ranges were determined with a refractive index of 1.245 to ensure the accuracy of the particle count result. A 10:1 aerosol diluter (TSI model 3332, Shoreview, MN) was installed before the inlet on the OPS to ensure the accuracy of the measurement. It should be noted that limited water-only testing was conducted to assess the impact of spray water droplets on OPS particle counting and that the spray droplet had no impact.

Before each test, the chamber was sealed and the spray was operated to wet the interior walls. Dust was injected into the chamber until the instantaneous concentration reached at least 100 mg/m^3. The spray was tested at designated water pressures and testing was started once the dust concentration naturally decayed to approximately 100 mg/m^3. Water pressures of 100, 200, 400, 600, and 800 psi were evaluated. At the same time, the aerosol monitors and particle counter were started and operated continuously throughout the whole test period. Each test continued for 60 minutes or until the dust concentration reached below 1.0 mg/m^3. A randomized full factorial experimental design with three repetitions for each test condition was performed.

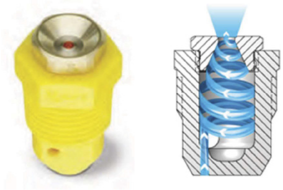


Figure 2. WhirlJet® BDM3 spray nozzle and working mechanism.

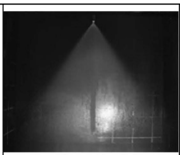
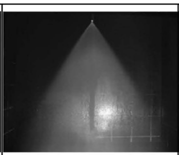
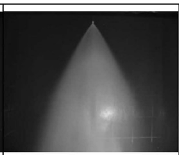
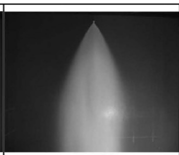
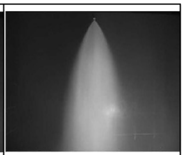
3 ANALYSIS OF THE SPRAY NOZZLE CHARACTERISTICS

The water flow rates and spray angles under different pressures operated in the chamber were measured and are listed in Table 1. It is obvious as the water pressure increases, the water volume sprayed out from the nozzle increased, but the spray angle narrowed down. With a smaller spray angle, a smaller spray coverage (area or volume) in the chamber can be expected as well. As can be observed from the spray pattern, the plume bottom converged considerably starting from 400 psi. This convergence started closer to the nozzle tip under higher pressures. This divergence effect can reduce the actual spray coverage from the spray angle based on theoretical coverage calculations.

4 RESPIRABLE DUST KNOCKDOWN PERFORMANCE EVALUATION

Figure 3 shows the respirable dust concentration (solid line) and cumulative water consumption (dashed line) results for tests under different pressures over the testing period. The dust concentration dropped sharply for all pressures within the first 10 minutes, then it slowly decreased to the ending concentration. Under spray pressure 100 and 200 psi, the final dust concentration reached 8.70 and 2.77 mg/m^3, respectively. While under higher pressure, the final dust concentrations were able to reach the 1.0 mg/m^3 stop criteria, and the time it takes to reach this criterion for tests with spray pressures of 400, 600, and 800 psi are 30.8, 13.7, and 8.3 minutes, respectively.

Table 1. Spray specifications and characteristics of WhirlJet® BDM3 hollow cone spray under different water pressure.

Spray Image					
Pressure psi	100	200	400	600	800
Water flow gpm	0.80	1.17	1.59	1.92	2.21
Spray angle degree	74.7	72.1	65.6	58.0	52.4

Note: The spray angles were measured at approximately 20 inches from the nozzle tip

These results were anticipated because more water was sprayed into the chamber under higher spray pressure. Evidence can be found from the dashed lines in Figure 3 that the cumulative water consumption for higher pressure is always higher than lower pressure tests. However, since high-pressure spray is more effective on capturing dust, the total water consumption to realize the same dust reduction for high pressure is much smaller. For example, to realize 90 % dust reduction, the total water consumption under 100, 200, 400, 600, and 800-psi spray pressures is 41.7, 20.1, 10.2, 7.4, and 5.9 gallon, respectively.

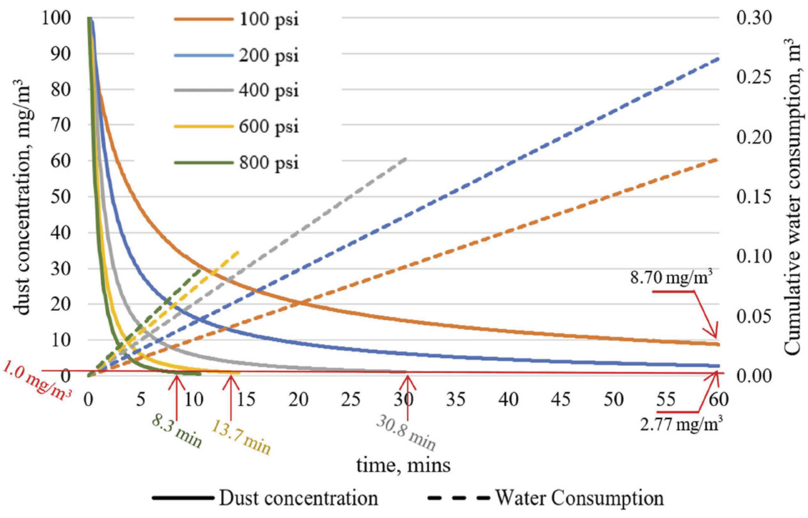


Figure 3. Respirable dust concentration for BDM3 under different pressures.

5 SUPPRESSION EFFECTIVENESS EVALUATION FOR SUBMICRON PARTICULATES

A previous study (Jiang et al., 2022) addressed the issue of low capture efficiency for submicron particulates by water sprays. The results revealed that under 100-psi spray pressure, particles under 1 µm can remain airborne through the 60-minute test, and particles under 0.5 µm can be considered irremovable particles under the same condition. Therefore, this section analyzes the submicron particulate suppression performance under different spray pressures. Since size channels for the particle counter were calculated with a refractive index, the cap size was not rounded at 1 micron. It should also be noted that each size bin is represented by its top size range, which means bin 0.374 µm indicates a particulate size in the 0.3 to 0.374 µm range.

Figure 4 plots the sub-1.117-µm particle counts during the whole testing process under different spray pressures. A particle count peak can be found under each pressure within the first 10 minutes of spray. These peaks were likely caused by resuspension of the residual dust in the chamber by the spray action. Based on the ending counts from different pressures, it appears that submicrons can be suppressed by higher spray pressures in a relatively short period of time. It took around 6, 10, and 24 minutes for spray pressure of 800, 600, and 400 psi to reduce 80 % of submicrons from their peak. The final reduction percentage of submicrons under 200 and 100 psi are 69.4 and 41.6 %, respectively. These results agree with findings from other studies that the wettability of submicrons is lower than larger sizes (Yu et al., 2020). Considering the short interaction period of spray and particulate in the underground face, and it can be expected that most submicrons are likely to escape from low-pressure open sprays and enter the mine atmosphere.

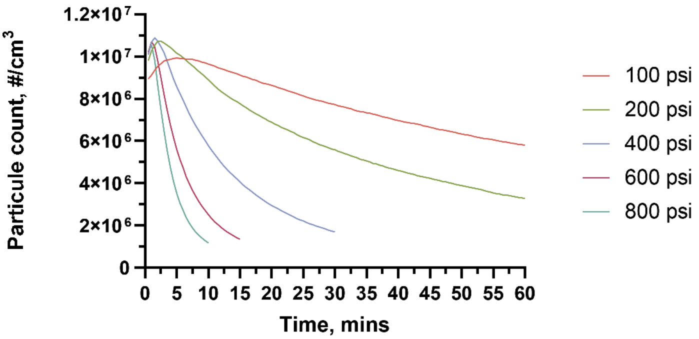


Figure 4. Sub-1.117-µm particle count results under different spray pressures.

In addition to the sub-1.117-µm particle count results, the detailed particle count results for 7 size bins at different time stamps (shown by various colors) under different pressures are plotted in Figures 5, 6, and 7. The y-axis is the dust counter result percentage at the time compared to its initial count.

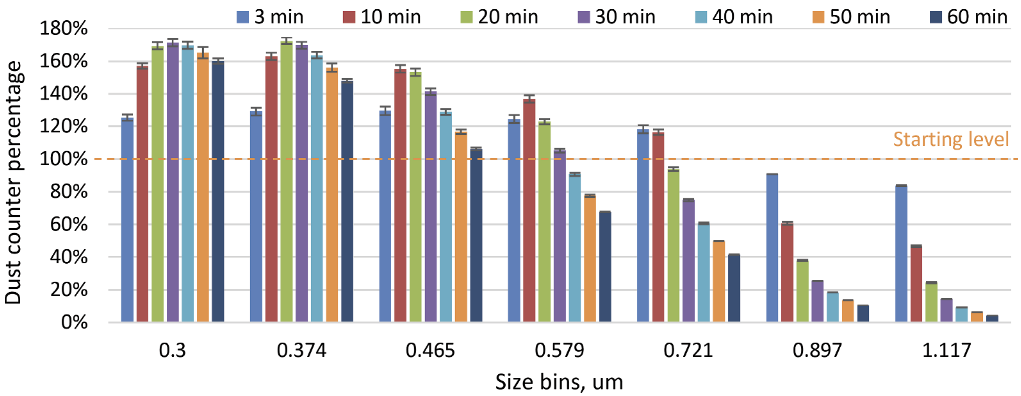


Figure 5. Sub-1.117-particle count results under 100-psi spray water pressure (mean ± SD, n=3).

Resuspension of particles were observed after 3 minutes of spray under all pressure levels. The observed size range for particle resuspension is narrower for higher pressure spray than

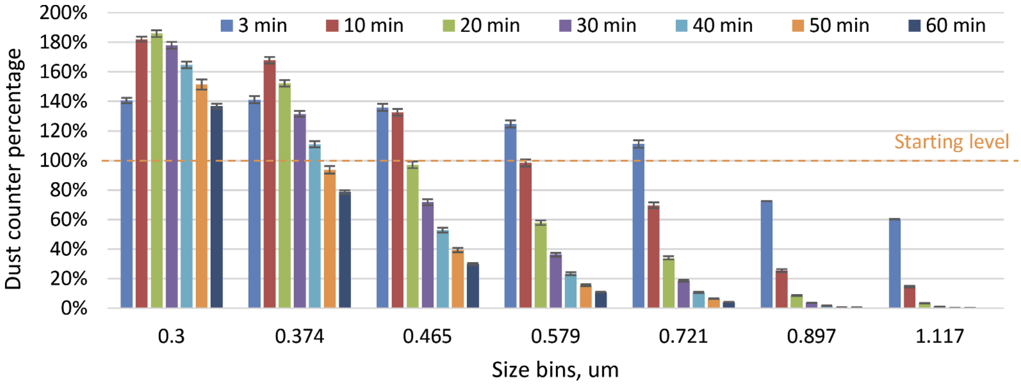


Figure 6. Sub-1.117-particle count results under 200-psi spray water pressure (mean ± SD, n=3).

lower pressure spray. At 100-psi spray pressure, the size range for resuspension is 0 to 0.721 µm, while the range under 800 psi is below 0.374 µm. These figures also show that when the peak of particle resuspension is reached at different times after spraying begins, it takes longer to reach the peak under low-pressure spray—at 100 psi it took almost 30 minutes to fully resuspend the sub-0.3-µm particles. It should be noted that under a 100-psi and 200-psi spray pressure condition, there is a substantial amount of dust remaining above the initial level after a 60-minute test. The knockdown efficiency for that size range under these pressures is so low that after 60-minute test, the ending particle count is still higher than when the spray begins.

Because the spray water droplet and dust interaction period is less than 3 minutes in the production face, the size boundary for effective suppression can be identified from the dust counter results. The lower boundary can be found when the counter results at 3 minutes in that size bin are lower than the starting level. Using this criterion, the lowest effective suppression size boundary for this spray under different pressures can be identified as 0.897 µm for both 100 and 200 psi, 0.721 µm for 400 psi, and 0.465 µm for both 600 and 800 psi.

The above results indicate a low capture efficiency and high resuspension possibility for particles under micron scale or nano-scale. In recent years, nano-scale dust particles and their aggregates or agglomerates have obtained significant attention due to their potential influence on the health of workers. Based on the analysis of coal dust samples collected from several underground coal mines, the presence of Coal Dust NanoParticles (CD-NPs, smaller than 500 um) have been confirmed (Keles, et al., 2022). Studies have examined and compared the differences in physicochemical properties, the acute pulmonary toxicity, and the chronic pulmonary

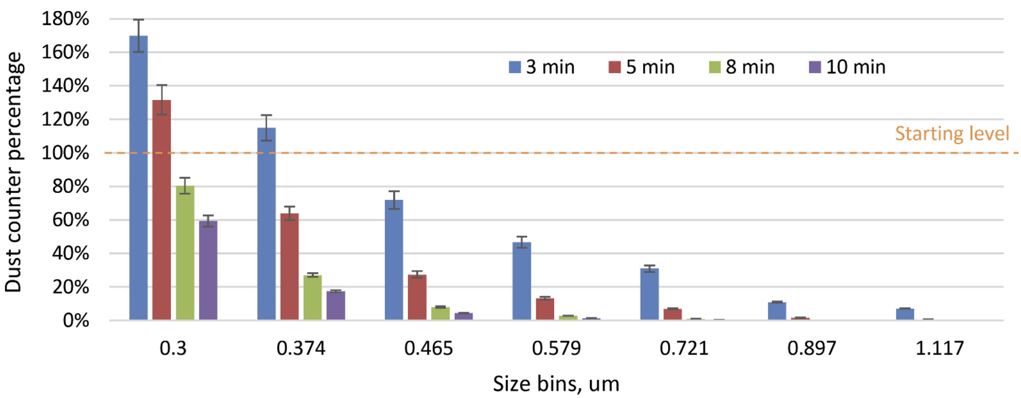


Figure 7. Sub-1.117-particle count results under 800-psi spray water pressure (mean ± SD, n=3).

fibrosis-inducing ability of Coal Dust Micron Particles (CD-MPs, smaller than 5 μm) and CD-NPs as well as their adverse effects of coal dust size on the lung (Zhang, et al., 2022). Findings indicate that CD-NPs are more chronically toxic than CD-MPs due to a lower oxygen-to-carbon ratio, smaller size, and larger surface area based on characterization analysis of particles. Other researchers also conclude that CD-NPs pose a higher risk to human health and cause a larger surface area with a different toxicology compared to the same mass concentration of dust of a relatively large size (Fan and Liu, 2021). Though it has been proven that submicron particles are difficult to capture by water sprays, their flow path can be easily manipulated by air stream. This means that these particles can be easily isolated from workers by ventilation design. In this case, there will be advantages to using the air-moving properties of the spray rather than the suppression ability.

6 CONCLUSION

Laboratory tests were conducted in a 512-ft^3 dust chamber with the WhirlJet® BDM3 hollow cone spray to study its respirable dust removal performance at five different water pressure levels ranging from 100 to 800 psi. For each test, the respirable dust concentration and particle count were continuously monitored during the 60-min spray application or when the dust concentration dropped below 1.0 mg/m^3. Results show that the total water consumption to achieve the same dust reduction under high pressure is smaller than a low-pressure spray. The suppression effectiveness of submicron particulates was also evaluated in this study. The final reduction percentages of submicrons under 100 and 200 psi are 41.6 % and 69.4 %, respectively. The lowest suppression effective size boundary from 100 to 800 psi is between 0.897 to 0.465 μm.

The resuspension of submicron particles was observed under all spray pressure levels, and the cap size for particle resuspension is lower for a higher-pressure spray than for a lower-pressure spray. There is a substantial amount of submicron particles that remain airborne after a 60-minute spray test, especially for the low-pressure condition. Overall, results show a low capture efficiency and high resuspension possibility for micron- or nano-scale particles under the testing conditions. Considering the adverse effect of smaller particles on lung function and the higher risk to human health compared to the same mass concentration of dust with a relatively larger size, other mitigation methods or ventilation tools should be used to address this problem.

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 (NIOSH), Centers for Disease Control and Prevention (CDC). Mention of any company or product does not constitute endorsement by NIOSH.

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