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A LABORATORY STUDY OF THE DUST DEPOSITION AND SUPPRESSION PROCESS FOR RESPIRABLE COAL DUST IN A CONFINED CHAMBER

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ABSTRACT

Respirable coal dust has been long recognized as a leading cause of multiple lung diseases. Efforts aimed at reducing dust concentration in underground mines have been made, but increases in coal workers' pneumoconiosis incidence rates over the last 20 years among U.S. miners are concerning. Dust deposition and water spray suppression are two types of dust removal mechanisms in underground mining activities. In this study, laboratory tests were conducted to investigate the respirable dust decay characteristics during deposition and suppression processes in a confined dust chamber. Dust concentration and size distribution were monitored continuously throughout each 60-minute test. A number-basis particle size distribution was used for analysis to capture the changes of smaller size fractions within the investigated dust sample. This study found that around 62.1% of respirable dust particles were deposited at the end of the deposition test. In addition, the final deposition rate for very fine particles can be less than 20%. The results from the suppression test indicate that larger particles were removed quickly; however, sub-micron particles remain suspended through the 60-minute water spray, and particles under 0.5 μm can be considered irremovable dust under single-spray operation conditions. This study also observed the resuspension of a significant amount of sub-micron particles by the water spray. The results of this study provide basic information for improving dust control strategies and can be utilized to improve the water spray performance for reducing airborne dust levels.

INTRODUCTION

Coal mine dust control is one of the main challenges to safe coal production. It has long been recognized that exposure to respirable coal and crystalline silica dust can cause pneumoconiosis and silicosis in coal miners [1]. Fine particles, less than 10 μm in diameter (all particle sizes are in aerodynamic diameter unless expressed otherwise) are generally able to reach the alveolar region in the lung and are called respirable dust [2]. Efforts aimed at understanding and reducing coal workers' pneumoconiosis have been made in recent years, but increases in incidence rates among U.S. miners is still concerning [3].

In recent years, particles with a nominal mean aerodynamic diameter ≤ 2.5 μm have drawn great attention by the public due to their high penetration efficiency into the lower respiratory tract. Miller et al. specifically recommended a particle size cut-point of ≤ 2.5 μm as an indicator for fine particulate matter based on consideration of particle penetration into the gas-exchange region [4]. For particles under 2.5 μm, tracheobronchial deposition efficiency through nasal and mouth breathing for an adult male engaged in light exercise can be 30% and 94%, respectively [5]. This percentage can be even higher when considering a coal miner's high work intensity. Such high tracheobronchial deposition efficiency shows that fine particles under this size range pose a greater risk to human health. Dust intervention techniques were developed and implemented in underground mines to reduce the exposure of fine particles.

Dust deposition and suppression are two types of dust removal mechanisms in underground mining activities [6]. Dust deposition is the spontaneous attachment of particles to surfaces. The fundamental physical processes of airborne particles transported onto surfaces include: Brownian diffusion, turbulent diffusion, drag force, gravitational settling, thermophoresis, electrostatic force and turbophoresis [7]. In a common underground mining environment, all these processes can apply except for electrostatic force because of a lack of an electrical field. However, the deposited particles may also be released due to modification in flow conditions or other disturbances. Particle deposition rate (or aerosol removal rate) is a commonly used parameter to quantitatively characterize the rate of deposition. This parameter incorporates all the deposition processes on all surfaces with different orientations that removes aerosols from being suspended. The particle deposition rate in an enclosure can be expressed by the following equation [8]:

$$\frac{dC(d_p,t)}{dt} = -\beta C \qquad (1)$$

Where $C(d_p, t)$ is the aerosol number or mass concentration as a function of time in the core region of an enclosure, and β is the particle deposition rate or particle decay rate with the unit of time^{-1}. This equation is developed to evaluate the deposition rate in enclosed spaces, and not many published studies have investigated the dust deposition onto surfaces in an underground coal mining condition, probably due, in part, to the relatively small amount of deposition compared to other dedusting mechanisms.

Water sprays are the most simple and economical method for dust suppression and have made significant contribution toward reducing respirable dust exposure for underground coal personnel. Water spray systems are embedded on longwall shearers, continuous miners, and hydraulic shields with different types and configurations [9]. Dozens of sprays are mounted across the mining machine based on different purposes. Scholars have studied different spray configurations and controls to optimize the spray dust reduction system on mining machines [10, 11]. Most commonly, hollow cone sprays with an operating pressure between 60 to 150 psi can be found in underground mining operations.

Previous water spray studies have shown differences in dust removal efficiencies for various nozzle types [12, 13]. Higher rates of dust removal per unit of water usage were found for air-atomized and hollow cone nozzles. Other parameters, such as nozzle orifice, operating pressure, and air induction capacity are found to be quite influential to the dust removal rates as well [14, 15]. It is commonly accepted that smaller orifice and higher operating pressure tend to generate smaller water drops which could enhance the dust removal rates [16, 17].

In this study, the respirable dust decay characteristics were investigated for both the deposition and water spray suppression process. These two processes were evaluated by a similar research method, and the deposition test can create a baseline for spray suppression result analysis. The results of this study provide basic

information for improving dust control strategies and can be utilized to improve the water spray performance for reducing airborne dust levels.

LABORATORY EXPERIMENTAL SYSTEM AND SCHEME

Dust chamber experimental system

A confined chamber dust removal evaluation approach was used to investigate the respirable dust deposition characteristics in a static air environment and dust suppression effectiveness for a water spray [18]. The advantage of this confined chamber approach compared with open-ended duct approach is that dust was only introduced at the beginning of the test to reach an initial concentration instead of a constant dust source throughout the test.

A 512-ft^3 dust chamber (8 ft by 8 ft by 8 ft) constructed of plywood was used for testing. A drain was installed in the bottom corner. Dust 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 3/8" WhirlJet$^@$ BD-3 hollow cone spray nozzle was mounted at a 58-inch height on the centerline axis of the chamber [19]. This spray nozzle was selected because of its high popularity in the mining industry and water use efficiency [20]. The typical operating pressure for this type of spray in underground mining equipment is between 60 and 100 psi based on different functions.

It should be noted that only respirable particles are of interest in this study, and the over-sized particles in the raw coal dust were removed by cyclone during the sampling process for dust concentration measurement instruments. 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 was operated as an all-time survey instrument, and the dust concentration was continuously recorded by the other two real-time aerosol monitors 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. 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. 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.

Keystone Mineral Black 325 BA coal dust (Keystone Filler & Mfg. Co., Muncy, PA) was used as the testing media. By volume, 65% of the particles are less than 10 μm. The dust size distribution for the respirable fraction measured by the OPS is shown in Figure 1. The solid lines represent the cumulative particle size distributions for number- and volume-basis, and the column represents the number-basis frequency of particles within each size bin. The stated size for each bin represents the top size for that bin. A different impression can be imparted from a volume-basis size distribution to a number-basis one as shown below. The advantage of a number-basis distribution is that it makes it possible to capture the changes in small particles. For example, in this case, particles below 1.117 μm accounted for only 0.3% in volume-basis distribution, while the distribution for the same size range goes to 68.4% when using the number standard.

Scheme of dust deposition and suppression tests

For dust deposition testing, the chamber walls were wetted before each test, and no air movements were anticipated in the confined chamber during the test. First, dust was injected into the chamber until the instantaneous concentration reached at least 100 mg/m^3. It should be stated that all dust concentrations are the relative mass concentration measured by an aerosol monitor instrument unless expressed otherwise. After the dust concentration naturally decayed to approximately 100 mg/m^3, the continuous aerosol monitors and particle

counter were started and operated continuously for 60 minutes. Test procedures for the dust suppression test were exactly the same as the deposition test, except the spray was activated at the same time as the measuring instruments. Plain municipal water was used, and the operating water pressure for the spray was set to be 100 psi (±1%). Three repetitions of each test were conducted.
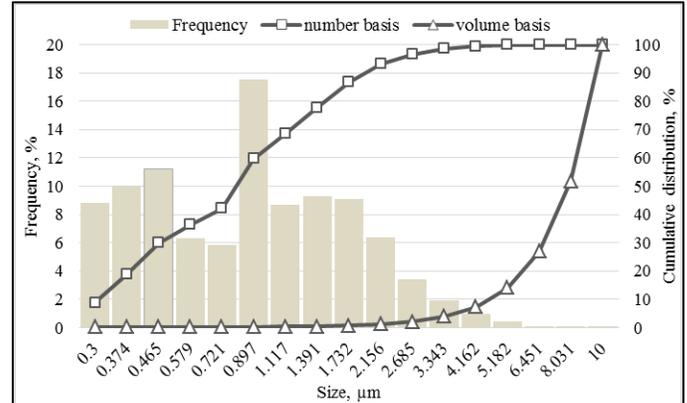

Figure 1. Dust particle size distribution for the introduced dust.

By employing this test method, the dust deposition and spray dust removal characteristics during the test period can be investigated. The dust decay rate was employed for evaluating both deposition and suppression, determined by the following equation:

$$C_t = C_0 e^{-\beta t} \qquad (2)$$

By rearrangement, this equation can be written as:

$$\beta = -\frac{ln^{C_t}/_{C_0}}{t} \qquad (3)$$

Where β is the dust decay rate with the unit of time^{-1} (e.g., min^{-1}), t is time, C_0 is the initial dust concentration in the unit of mg/m^3, and C_t is the dust concentration at time t in the unit of mg/m^3.

RESULTS AND ANALYSIS OF DUST CONCENTRATION AND SIZE DISTRIBUTION

Respirable dust concentrations

Figure 2 shows the respirable dust concentration results for dust deposition and suppression tests. Variations in experiments are shown by standard deviations. The trends of dust concentration in both deposition and suppression tests are similar, dropping rapidly at first and then gradually decreasing afterward. After the 60-minute deposition and suppression process, the final dust concentrations represent dust reductions of 62.1% and 91.4%, respectively.
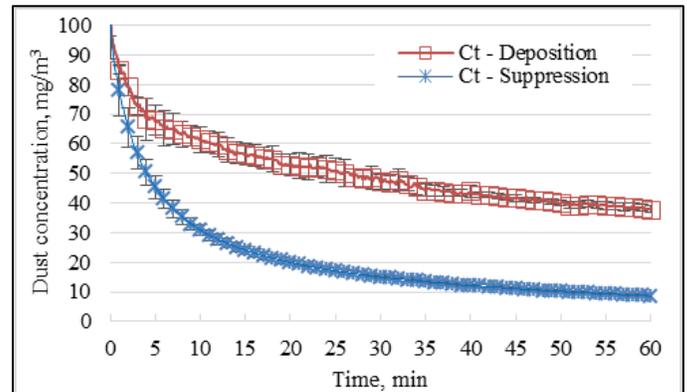

Figure 2. Dust concentrations for deposition and suppression tests.

Figure 3 shows the plotted dust decay rate and normalized reduction rate (C_p). The β for deposition test drops to almost 0 in the first 7 minutes and fluctuates mainly between -0.02 to 0.02 min-1 thenceforth. For the spray suppression test, the dust decay rate

decreases sharply at first and then slowly approaches zero. This orange curve in Figure 3 fits to a power function (Eq. 4) listed below with R = 0.9268. It should be noted that the graph for a negative power function will approach but never equal zero.

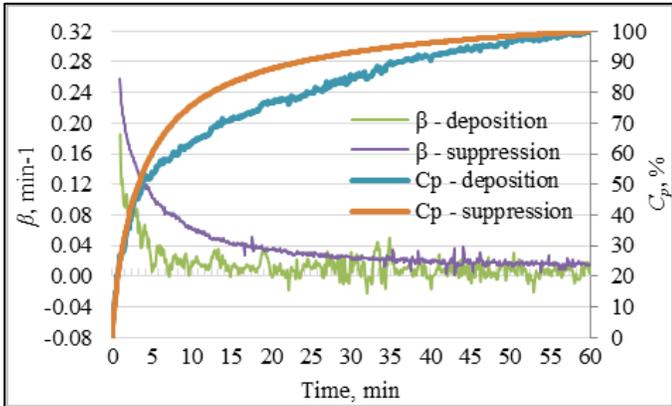$$\beta_{dep} = 2.4892t^{-0.783} \tag{4}$$

Figure 3. Dust decay characteristics for deposition and suppression tests.

C_p was calculated based on Equation (5). This index can visualize the reduction rate compared to its total reduction during the process, where C_f is the final dust concentration in the unit of mg/m³. Both C_p rates were over 50% within 4 minutes, meaning half of the total reduction takes place in the first 4 minutes for both deposition and suppression. However, for deposition, 4 minutes is the turning point for the reduction rate, where the slope for C_p turns flatter until the end. Meanwhile, the slope for C_p in the suppression test shifted to a slower rate at around 15 minutes. More than 83% total reduction was realized in 15 minutes.

$$C_p = \frac{reduction\ at\ time}{total\ reduction} = \frac{c_0 - c_t}{c_f - c_0} \tag{5}$$

Dust size distributions

Figure 4 illustrated the particle count at the end of both tests compared to the initial distribution. For deposition test, all particles are deposited at a slow rate, while smaller particles deposited slower than larger particles. Based on the values provided in Table 1, after a 60-minute deposition process, the reduction for smaller particles sized less than 0.721 µm are all below 22%, while particles between 0.721 to 8.031 µm saw reductions of 33 to 55%.
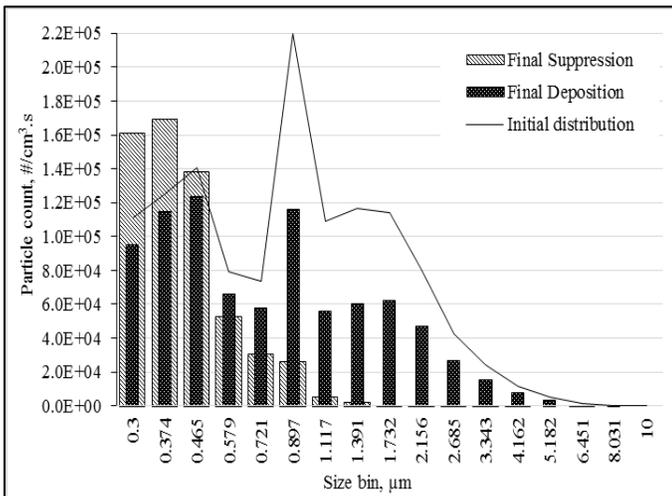

Figure 4. Final dust size distribution for deposition and suppression test.

As shown by the final suppression particle counts in this figure, more than 95% of particles larger than 1.117 were suppressed during the 60-minute spray application. However, 11.8% of particles within the 0.897-µm size bin remained airborne. A larger fraction of smaller particles was still suspended, as the reduction percentages for particles within the 0.579-µm and 0.721-µm size bins were 34.7% and 58.2%, respectively. The number of particles within the 0.465-µm size bin was barely changed. In addition, the final particle number for under 0.374 µm was higher than the initial number by as much as 44.8%. This indicates that a considerable number of these sub-micron particles were resuspended from the environment. It should be noted that even though number-wise this increase is quite influential, considering the small volume and weight of these particles, it does not account for a substantial fraction within the final dust concentration.

Table 1. Dust count (#/cm³·s) results for deposition and suppression test*.

Size Bin (µm)	Initial Count	Deposition Test Count	Deposition Test Reduction	Suppression Test Count	Suppression Test Reduction
< 0.3	110656	94803	14.3%	160256	-44.8%
0.374	125136	114418	8.6%	167766	-34.1%
0.465	140615	123483	12.2%	137513	2.2%
0.579	79565	66163	16.8%	51941	34.7%
0.721	73445	57375	21.9%	30703	58.2%
0.897	219739	116051	47.2%	25948	88.2%
1.117	109303	55586	49.1%	5174	95.3%
1.391	116788	60389	48.3%	1751	98.5%
1.732	113904	62268	45.3%	280	99.8%
2.156	80377	47110	41.4%	20	100.0%
2.685	42711	26671	37.6%	2	100.0%
3.343	24049	15455	35.7%	1	100.0%
4.162	11836	7698	35.0%	0	100.0%
5.182	5104	3297	35.4%	0	100.0%
6.451	1138	755	33.7%	0	100.0%
8.031	115	51	55.5%	0	100.0%
10	3	0	100.0%	0	100.0%

*OPS counts in this table are 1/10 of actual due to the aerosol diluter.

The presence of resuspension can also be found in Figure 5. This figure plots the particle counts for each size bin during the whole suppression process. The resuspension was observed for particles smaller than 0.721 µm in size, as their particle count increased within the first 10 minutes after the spray started. The suspended particles between 0.465 to 0.721 µm were able to be captured by the spray afterwards, but much slower than large particles, and their final particle number dropped below initial level as the spray continued. However, it appears that the BD3 spray under 100-psi operating pressure was ineffective to remove particles smaller than 0.465 µm as their final quantities are higher than initial counts. In a mining environment, this resuspension can be more obvious due to lower humidity in the working area (depends on localized conditions) compared to the almost 100% humidity in the testing chamber. It should be noted that the resuspended dust fraction in this suppression test (the negative percentage in Table 1) counts around 20% in the final respirable dust concentration measurement (volumetric basis) based on a theoretical calculation.
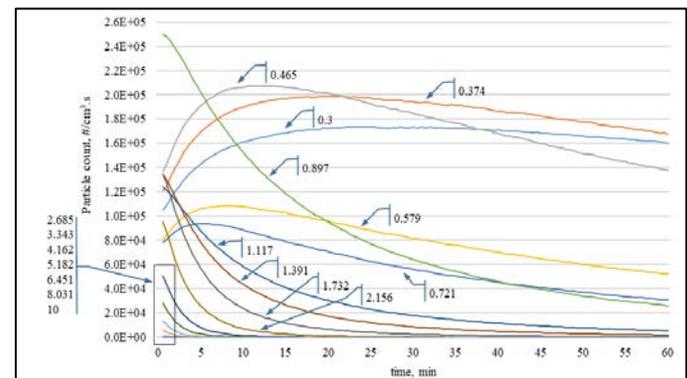

Figure 5. Particle counts with time for each size bin during suppression test.

Discussion of the characteristics of dust removal process by water spray

As indicated from the dust concentration results, the dust concentration dropped sharply in the first 10 minutes, which can be attributed to larger particles, specifically those particles over 2 µm in size. Evidence can be found from Figure 5 that the number for particles over 2.156 µm dropped substantially during the same period.

In regard to particle size, larger particles were removed more effectively than the smaller particles. In general, particles around 2 µm were removed at a much slower rate than larger particles owing to their reduced removal efficiency. Particles under 1 µm remained suspended through a 60-minute spray, while particles under 0.5 µm can be considered irremovable dust under such condition because their reduction rate is less than 35% and potentially even negative. In other words, in an actual mining environment with the same spray settings, these particles likely cannot be captured by a single spray and can remain suspended for a very long time with no other interventions. The effect of multiple sprays was not investigated and may have a different impact on dust capture characteristics. These above-mentioned particles all belong to the sub-2.5 µm category. So, it's worth emphasizing that sub-2.5 µm particles have an over 90% deposition efficiency into the lower respiratory tract by mouth breathing, which poses a huge lung health risk to coal miners. The resuspended and irremovable sub-micron particles (≤ 1 µm) will not affect the whole dust concentration to any considerable extent due to their small weight and volume. But with the unclear result of their damage to a human being, this issue should be raised and is worth further research efforts.

CONCLUSIONS

In this study, dust deposition and suppression tests were conducted in a confined chamber. The respirable dust decay rate and particle size characteristics over a 60-minute testing period were investigated. In dust suppression testing, a BD3 spray nozzle operated at 100 psi was incorporated. A number-based particle size distribution was preferred, and this analyzing strategy was applied to observe the distribution change for ultra-small particles. The following conclusions can be obtained:

(1) A notable respirable dust deposition phenomenon was observed under this testing condition, as the dust concentration dropped from the initial 100 mg/m^3 to 37.9 mg/m^3 at the end of the 60-minute test. The dust concentration results from suppression testing fit to a power function with a negative power, where the graph will approach but never equal 0 over time. The final dust concentration after the 60-minute spray application was 8.6 mg/m^3.

(2) The sharp dust concentration reduction in the first 10 minutes during suppression testing was mainly due to the suppression of large particles. Even though the total concentration decreased considerably, the total number of particles, especially sub-micron particles (≤1 µm), increased due to resuspension. The final irremovable dust primarily consisted of these sub-micron particles.

(3) Based on the particle count results, more than 99.5% of particles sized larger than 1.117 µm were suppressed during the 60-minute spray at different rates. Larger particles were removed faster than the smaller particles. Particles below 2 µm were removed slower than larger particles due to their reduced removal efficiency. Generally, particles under 1 µm can remain suspended through the 60-minute water spray, and particles under 0.5 µm can be considered irremovable dust under such spray operation conditions. A potential future research area targeting the removal efficiency for ultra-fine particles by water spray could be beneficial to the overall dust control system.

(4) Resuspension was observed for particles smaller than 0.721 µm in size. The quantity of particles involved in this resuspension is significant, but their impact to the overall respirable dust concentration is limited because of their small weight and volume. In an underground mining environment, this resuspension could be more obvious due to less humidity in the working area.

DISCLAIMERS

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