A Preliminary Investigation of DPM Scavenging by Water Sprays

L. Rojas-Mendoza [a], E. McCullough [a], E. Sarver [a,*], J.R. Saylor [b]

[a] *Virginia Tech, Department of Mining and Minerals, Blacksburg, VA 24060, USA*
[b] *Clemson University, Department of Mechanical Engineering, Clemson, SC 29634, USA*

Diesel particulate matter (DPM) presents serious occupational health concerns, particularly in enclosed environments such as underground mines. Since 2002, DPM exposure in U.S. mines has been subject to regulations implemented by the Federal Mine Safety and Health Administration (MSHA). While current strategies to curb DPM exposures have been largely successful (e.g. improved ventilation and engine exhaust treatments), challenges still exist in some mine settings, particularly where relatively high airflows are not practicable. New technologies to remove DPM from such areas are needed. Water sprays have long been used in underground mine operations as part of comprehensive dust control programs. Indeed, significant research has been focused on the spray mechanisms for abating dust, with observations indicating that both material wetting and airborne-particle scavenging contribute to reductions in respirable dust concentrations. However, little attention has been given to the efficacy of spray droplets to scavenge DPM.

As part of a new Capacity Building in Ventilation project sponsored by the National Institute for Occupational Safety and Health (NIOSH), we aim to determine if and how water sprays might be used to control DPM in underground mines. This paper reviews DPM in the underground mine environment, airborne particle-water droplet interactions, and our research progress to date. The laboratory setup for experimental work is specifically described and several challenges are discussed, including dilution of the engine exhaust stream to achieve a steady supply of DPM under flow conditions compatible with analytical instruments.

Keywords: Diesel Particulate Matter, DPM, Water Sprays, Scavenging, Nanoparticles

1. Introduction

Diesel particulate matter (DPM) is a component of diesel exhaust that is hazardous to human health. It is classified by EPA and OSHA as a potential or suspected carcinogen [1, 2]. The type and severity of harm is dependent upon two factors: the amount of DPM to which a person is exposed, and the duration of the exposure [1]. Physical symptoms range from minor discomforts such as headaches and eye irritation under acute exposure, and major cardiovascular and pulmonary diseases (e.g., lung inflammation) under long term exposure [1-3]. Epidemiological studies demonstrate a relationship between DPM exposure and increased lung cancer rates. These increased lung cancer rates could be caused by polycyclic aromatic hydrocarbons (PAH) present in diesel exhaust [3]. However, specific mechanisms for health impacts from DPM exposures are not fully understood, particularly the adverse impacts of nanoparticles [3, 5]. Nanoparticle research is a significant priority because pulmonary deposition increases with decreasing particle sizes, and because some chemicals that are innocuous at larger sizes can be toxic at the nanoscale [4].

Underground miners represent a particularly high-risk population when it comes to DPM exposures [5], because of the heavy diesel powered equipment used in the enclosed environments where they work [6, 7]. In metal and nonmetal mines (M/NM), ventilation challenges (e.g., low air flows, leakage, recirculation) can make DPM so difficult to abate, that it becomes a restrictive variable for mining planning and operation [7-9].

In the US, issues related to occupational health of miners are covered by the Mine Safety and Health Administration (MSHA) [2, 6]. Regulation pertaining to permissible personal exposures in M/NM mines is found in the Code of Federal Regulation (CFR) from 30 CFR 57.5060 to 30 CFR 57.5075. DPM exposure limits have been regulated since 2002 [8], and the final personal exposure limit (PEL) became effective on May 20, 2008 [9]. It mandates that a miner's exposure to DPM must not exceed an average eight-hour equivalent full shift airborne concentration of 160 $\mu g/m^3$ (on the basis of total carbon, TC) [10]. In general, noncompliance can be determined by use of a single sample collected and analyzed per the CFR [11]. The CFR also limits the amount of sulfur permitted in diesel fuel and the type of additives that can be used, and requires mine operators to monitor "as often as necessary" the concentration of DPM to protect miner health [13, 14].

1.1 DPM Characteristics

Diesel exhaust is composed of two phases, both of which contribute to occupational health risks: gas and solid particles [4, 5, 10]. The gaseous phase includes compounds such as CO, CO_2, NO_x, SO_x and a number of hydrocarbons [6, 15]. The solid phase is mainly composed of highly agglomerated carbonaceous material and ash, in addition to volatile sulfur and organic compounds [4]. The carbonaceous material is comprised

author's email: esarver@vt.edu

of elemental carbon (EC) or soot and organic carbon (OC) [5]. TC is the sum of the EC and OC portions [6, 16]. The volatile organic fraction is the consequence of unburned fuel and lube oil, while sulfuric acid and sulfate particles are created from oxidation of SO_2 [5, 6].

Beyond classification by chemistry, DPM can be also be divided into size ranges based on aerodynamic diameter (AD), which is defined as the diameter of a 1g/cm^3 density sphere of the same settling velocity (in air) as the particle of interest [4, 15]. Fine particles are generally those with AD <2.5μm, ultrafine particles are those with AD <0.1μm (100nm), and nano-particles are those with AD < 0.05μm (50nm) [4, 5].

Based on size and formation mechanism, DPM particles can be classified in one of three typical modes: nuclei, accumulation, or coarse [4,15]. The nuclei mode is mostly composed of volatile organic and sulfur compounds residing in the nanoparticle range between about 0.003-0.03μm (i.e., in the general region shown as "1" in Figure 1) [15]. These particles are formed in the engine during the exhaust dilution and cooling [14], which make their characteristics highly variable, depending on engine operation, dilution and sampling conditions [4, 5, 17]. These particles only account for 0.1 to 10% of the total mass, but around 90% of the total particle count [5, 15]. The accumulation mode includes submicron solids (carbonaceous agglomerates and adsorbed material) with diameters of roughly 0.030-0.5μm (i.e., in the general region "2" in Figure 1). This mode spans from the upper end of the nanoparticle range, through the superfine range, to the lower end of the fine range [4]. The transition between the accumulation and coarse mode is somewhat fuzzy, but occurs between 0.5-1μm. Finally, the coarse mode includes particles > 1μm (i.e., in the general region "3" in Figure 1), which are generated as a consequence of deposition and following re-entrainment of particles in the engine walls and sampling systems. Relatively few particles actually fall into this mode by number, but they account for about 5-20% of the total mass [15]. Based on mass, most DPM resides in the accumulation mode, while from a number perspective, most DPM particles are found in the nuclei mode [5, 15].This may present a safety concern because DPM is regulated on a mass basis – as is generally the case with all airborne particulates due to limitations of analytical methods – but some health effects may be strongly influenced by nanoparticle exposure [5].

1.2 DPM abatement in M/NM mines

Numerous efforts have been made to curb DPM exposure in underground M/NM mines (i.e., [7–10, 18, 19]). Both engineering and administrative controls exist. Administrative controls include modifications to operational procedures to decrease the DPM hazard. Limiting equipment speeds, restricting engine idling and identifying areas where no personal should be located are examples of such administrative controls [2, 6]. Engineering controls that are used consist of technical improvements that either reduce DPM generation (e.g., upgraded engine technologies, exhaust filters and preventative maintenance programs to minimize emissions) [2, 9], or reduce miner exposures (e.g., sealing equipment cabs, providing increased ventilation) [2, 6, 10, 11]. Indeed, increased ventilation is one of the simplest options for limiting DPM exposure in principle, however this is challenging in large-opening mines. In such environments, it may be impractical to significantly increase airflow or to introduce effective ventilation controls (i.e. permanent sealing, stoppings and curtains) [6]. NIOSH has conducted some research related to improved ventilation layouts for large-opening mines [e.g., 6–8, 18], but many operations will undoubtedly remain challenged to meet current (and any future) DPM exposure limits. Not only might these challenges result in instances of overexposures, but in many cases they may also constrain operational flexibility (e.g., in terms of production schedules, resource appropriation, etc.)

In light of the above, new technologies are needed for DPM abatement. Water sprays have long been used in mining environments to control airborne dusts [21, 22]. While few studies can be located in the published literature regarding the efficacy of sprays to reduce DPM, theory and very fundamental work on water droplet-particle interactions suggest that certain size ranges of DPM should be affected (i.e., [22–25]) .

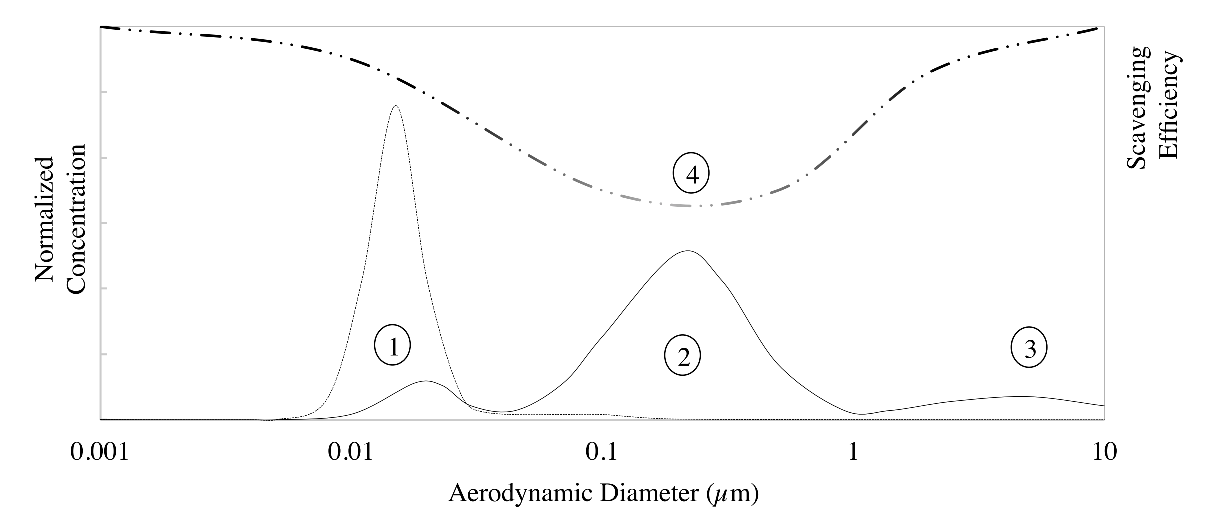


Fig 1. Illustrative depiction of DPM size distribution by number and by mass, and water droplet scavenging efficiency as a function of aerodynamic diameter. DPM size distribution (based on Kittelson (1997), [4]) exhibits three characteristic modes: Nuclei (shown as "1"), accumulation (shown as "2"), and coarse mode (shown as "3") For the scavenging efficiency (based on and Kim et al. (2001), [17]) the zone shown as "4" corresponds to an area where the efficiency reaches a minimum.

2. Sprays in Underground Mining

The concentration of airborne particles in underground mines is conventionally controlled by ventilation (i.e., via dilution and/or displacement), dust collector systems, and/or water sprays [22]. These techniques are ubiquitous in mining operations to control dust. Water sprays are often employed as part of a wet scrubber or as a local treatment by direct application to the zone of interest (i.e., nearby production areas and mineral processing installations) [18, 20, 23].

Water sprays are effective through two major mechanisms: wetting suppression and particle scavenging [17, 18] . Wetting suppression is the most common method of dust control at mine operations, and the premise is that particles are prevented from becoming airborne in the workplace. Wetting may be functional when it is applied to bulk materials, or when it limits particles previously deposited on walls and equipment surfaces from being liberated [21]. Wetting effectiveness can be enhanced by increasing wetting uniformity and the number of water sprays[22]. On the other hand the role of particle scavenging, also called collection, is to remove particles from the air. Mechanistically, the idea is for particles to collide with water droplets, and then to fall out of the air [20, 21, 24].

The scavenging efficiency is related to the ability of a drop or group of drops to capture airborne particles [24, 27]. This efficiency can be quantified by the scavenging coefficient (E), which is defined as the number of particles scavenged relative to the total number of particles that could have been scavenged by the spray. Practically, a coefficient can be calculated for certain size ranges or modes [28], or even certain types of particles. The scavenging efficiency depends on several characteristics of the water drop (i.e., density, diameter, charge, surface tension and viscosity), the particle (i.e., density, diameter and electrical charge) and also on the airflow and spray characteristics. Spray characteristics include the type of nozzle (e.g., geometry), operating pressure and flow rate [29]. The most common nozzle designs employed for dust abatement in the mining industry include: hollow cone pattern, full-cone pattern, and flat spray patterns [29]. Each of them produces different water drop diameters and mean velocities.

A fair amount of research has been conducted on water sprays for dust particles in the respirable range. It is widely accepted that the capture efficiency is directly proportional to the relative velocity between the spray droplets and the dust particles, and inversely proportional to the droplet diameters [24, 29]. Smaller water droplets can be obtained by using atomizing or fog sprays, steam sprays, electrically-atomized sprays and sonically atomized sprays [22]. Research due to Saylor et al., (2014) demonstrated that the scavenging efficiency for particles within the sub-micron range (i.e., 0.1-10μm) can be increased by using an ultrasonic standing-wave field [28]. However, it should be noted that the collection mechanism for dust particles might differ from the mechanism governing DPM scavenging since drop-particle interactions are size dependent.

2.1 DPM scavenging

There are four primary mechanisms of particle scavenging by water droplets: impaction; interception, Brownian diffusion and electrostatic attraction [22, 24, 30]. Impaction occurs when the path traveled by particles deviates from the flow streamlines due to particle inertia [26]. This mechanism depends on the Stokes number [26], and it plays an especially large role in spray scavenging of particles with diameters larger than 5μm [17]. Thus, impaction is the governing mechanism for airborne dust scavenging, but is not expected to significantly affect DPM. Interception occurs when a particle stays on the flow streamline but because of its finite diameter, touches the water droplet. The efficiency of particle scavenging by interception is directly proportional to the particle diameter and inversely proportional to the droplet diameter [24, 25]. Brownian diffusion, which refers to random motion of particles within a fluid, governs particle-droplet interactions for nanoparticles [25, 27, 30]. Indeed, the effect of interception and impaction are negligible for particles under 0.05μm, where around 90% of the number of DPM particles reside [17]. Finally, electrostatic attraction might also be important under conditions where DPM, water droplets or both possess sufficient electrical charge [26].

DPM scavenging will be highly dependent on particle-drop interactions [28]. Under fixed conditions of droplet diameter and particle-drop velocity, *E* should be related to the particle diameter [17]. Figure 1 provides an illustrative depiction of the overall scavenging efficiency as a function of the AD. This plot was developed based on research by Kim et al., (2001) that addressed scavenging via diffusion, interception and impaction [17]. As seen in the figure, for ultrafine and smaller particles (i.e., < 0.1μm) the scavenging efficiency increases as the particle diameter decreases, which is attributed to the growing influence of Brownian diffusion with decreasing particle diameter. For relatively large particles (i.e., > 1μm) *E* increases as particle size increases, due to the increasing effect of particle inertia with increasing particle size. Accordingly, for a certain size range in the middle (i.e., in the zone "4" in Figure 1) scavenging is very inefficient since this is where neither diffusive effects nor inertia are very effective. This range is known as the Greenfield gap [31]

While the discussion above suggests that at least some fraction of DPM should be subject to significant scavenging by water sprays, little practical research has been carried out along these lines. In fact, a thorough search of the literature turned up only two related studies. These are summarized in Table 1.

3. New Research

Clearly there is limited published research regarding DPM scavenging by water sprays. However, the few available studies indicate that for certain cases (e.g., neutral drop-neutral DPM) a fraction of the DPM can be affected. Additionally, the fundamental fluid mechanics of scavenging suggest that both small and large particles can be collected through different mechanisms.

It should be noted that, to a certain extent, removal of DPM by sprays and abatement of DPM by ventilation, act in opposition to each other. Spray scavenging works best when the distance between a drop and a particle is small, i.e. at high particle concentrations. Ventilation, on the other hand, seeks to reduce particle concentrations. One way to address this tradeoff is to separate the spray scavenging and ventilation activities. This could be done, for example, by creating a spray scrubber in regions of high DPM loading and then subsequently diluting the output of the scrubber via ventilation. Another approach is to optimize the power dedicated to DPM abatement, dividing it between ventilation blower power and spray pump power to maximize DPM removal.

Under a new Capacity Building in Ventilation project sponsored by CDC/NIOSH (contract no. 200-2014-59646), research in this area and others will be carried out to determine the efficacy of water sprays for scavenging DPM. This project officially began in September 2014 and will be developed over 5 years. Project tasks related to DPM scavenging by water sprays are outlined in Table 2.

Table 1. Summary of previous practical research on scavenging of combustion particles by water sprays. This table summarizes the work and results obtained in two different studies. The first study was conducted at the Universitá degli Studi di Napoli "Federico II" by L. D. Addio et al. (2013), [24]. The second study was conducted at Kobe University – Japan by T. Ha Hong et al. (2009), [23].

Research Study	Methodology	Major findings
'Removal of fine and ultrafine combustion derived particles in a wet electrostatic scrubber'' [24] • Developed by the Universitá degli Studi di Napoli " Federico II" • Determine the particle capture efficiency achieved in a wet electrostatic scrubber on particles ranging from 0.01-1µm.	• The source or particles was a naphtha lamp. • Water droplets and particles were charged with opposite polarities. • TSI 3910 and TSI 3340 were employed to determine particle concentration and distribution in the ranges 0.01-0.42μm and 0.09-0.74μm, respectively. • Efficiency was evaluated for the next three cases: a) Uncharged sprays and uncharged particles b) Uncharged particles and charged drops. c) Particles and drops charged with opposite polarity.	• For experiment "a" the efficiency was above 10% for particles finer than 0.22μm and almost null for coarser particles. Overall particle removal efficiency for experiment "a" was around 5%. • For experiment "b" the particle abatement reached an overall value of 35%, and for experiment "c" the overall efficiency reached 93%.
''Simultaneous removal of NOx and fine diesel particulate matter (DPM) by electrostatic water spraying'' [23] • Developed by Kobe University – Japan. • Evaluate the effectiveness of an electrostatic water spraying scrubber for the removal of NOx and DPM emissions in marine exhaust gas.	• A diesel engine was used as a stationary DPM emission source. • DPM was charged positive by using a corona power unity. • Stainless electrodes were employed to charge water droplets by induction. • An impactor (AS-500) was used to quantify DPM size distributions. Mass concentrations were obtained by weighting of filters. • Scrubber efficiency was evaluated at different engine loads for the next scenarios: a) No water spray (NS) b) Neutral drop-neutral DPM (ND-NP) c) Charged drop-neutral DPM (CD-NP) d) Charged DPM-neutral drop (CP-ND) e) Charged drop-charged DPM (CD-CP)	• DPM mass concentration increased when engine load increased. • ND-NP mass based scavenging efficiency roughly ranged from 10 to 20% for different engine loads. • Mass based efficiency increased for the other scenarios. CD-NP < CP-ND < CD-CP. • The mass-based scavenging efficiency showed to be directly proportional to the voltage applied for charged particles and drops.

3.1 Experimental setup and considerations

The experimental setup is shown in Figure 2 and consists of four main parts: A diesel engine as DPM source; a scavenging box (which includes the water spray system) to produce water droplets that can interact with DPM; particle counters on either side of the box to determine the efficiency of scavenging under different scenarios; and a number of devices allowing for system monitoring and control (e.g., pressure gauges, flowmeters). The most significant challenges to building and running the lab experimental system are environmental health and safety constraints, influence of dilution conditions on DPM concentration, protection of the particle counters (i.e., from overwhelming concentrations or pressures) and control of the water spray parameters.

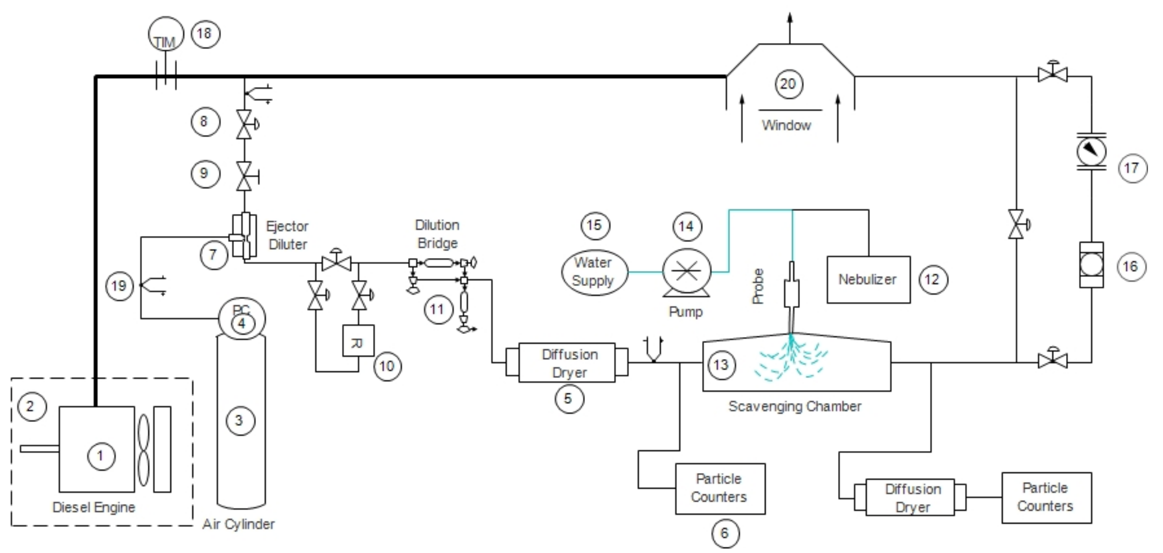
The DPM source employed for research purposes is a small diesel engine (component 1 in Figure 2). The main environmental concern regarding operation of a diesel engine indoors stems from the potential emissions into the laboratory space. Additionally, noise must be limited. The chosen engine creates low noise levels when run at 800 to 1000 rpm [32]; and an enclosure (the dashed lines in component 2 of Figure 2) with foam insulation material glued on the internal walls will provide additional assurance.

Table 2. Description of project tasks related to DPM scavenging by water sprays.

Task	Description and Variables
1) Construction of laboratory setup for spray/ventilation tests (Year 1)	• Design of the lab set up. • Identifying and acquiring the main components of the system: o Source of DPM -diesel engine. o Particle counters. o Scavenging box. o Water spray system. o Miscellaneous (i.e. flowmeters, filters) • Identifying and meeting environmental work space requirements. • Construction of lab set up. • Debugging and troubleshooting of lab set up.
2) Small-scale testing of water sprays on DPM scavenging (Year 2)	• Gathering data related to the overall scavenging efficiency of the water spray system. • Determining scavenging efficiency as a function of DPM diameter. • Testing on a small fraction of the engine exhaust (e.g., 1-10%) • Variables: o Spray atomization rate. o Dilution rate. o Airflow reaching the scavenging box (dilution rate & bleed-off fraction)
3) Large-scale testing of water sprays on DPM scavenging (Years 3-4)	• Adjusting lab set up for large-scale testing. • Experiments will be conducted on progressively larger fractions of the exhaust stream. • Determining the scavenging coefficient for the total amount of DPM for each particle diameter. • Additional Variables: o Engine operating load. o Flow temperature.
4) Field testing of water sprays (Year 4)	• The scavenging box will be decoupled from the DPM source and tested in an actual mining environment.

The enclosure will also serve to reduce vibrations and prevent accidental contact with the engine. A fan is located on top of the enclosure to guarantee enough air circulation to prevent overheating. A thermal insertion meter (18 in Figure 2) will also be employed to measure the total exhaust volume, which should fall between 30 and 40 CFM. The primary diesel exhaust (and the water-spray treated fraction of exhaust) will be piped out of the lab via a window (20 in Figure 2). DPM and CO monitors will be employed in several locations of the lab to monitor for exhaust leakage.

Dilution conditions influence the number of DPM particles in the system, especially for particles with AD lower than 0.1µm [18]. Conditions affecting the nucleation rate of DPM particles are dilution temperature, dilution ratio, residence time, relative humidity and sulfur content [5, 15, 17]. Sulfur content will be managed by use of a consistent fuel source and temperature through the installation of thermocouples (19 in Figure 2), however the other variables will require careful control and monitoring in order to guarantee repeatable conditions – and therefore reproducibility of data. A fractional bleed-off will be taken from the main exhaust by using a dilution ejector (7 in Figure 2). A dilution ejector is a vacuum generator that serves two purposes: first to guarantee that DPM is drawn into the system and second to allow for the dilution of the DPM stream with compressed air. A set of on/off control valves will be installed downstream of the ejector diluter. The on/off valve (8 in Figure 2) will allow the control valve (9 in Figure 2) to remain fixed once the desired flow has been reached. Dilution will be primarily controlled by mixing high-purity dry air (3 in Figure 2) with the exhaust bleed-off. Additionally, a dilution "bridge" (11 in Figure 2) will be incorporated to drop the DPM concentration to readable levels for the particle counters. The bridge reduces concentration by selectively filtering a fraction of the bleed-off flow [33]. The dilution bridge will also operate as an open vent to keep the system pressure at, near, or only slightly over atmospheric pressure to prevent overpressure of the particle counters.



Legend of components

1 Diesel Engine
2 Soundproof Enclosure
3 Gas Bottle
4 Pressure Regulator
5 Diffusion Dryer
6 Particle Counters
7 Ejector Diluter
8 On/off Valve
9 Control Valve
10 Rotameter
11 Dilution Bridge
12 Nebulizer
13 Scavenging Chamber
14 Peristaltic Pump
15 Water Supply
16 Filter
17 Flowmeter
18 Thermal Insertion Meter
19 Termocouple
20 Window

Fig 2. Preliminary design for DPM scavenging experiments using a water spray system and list of key components.

At the scavenging box, a tee will be used to direct one fraction of the diluted flow to the scavenging box while the remaining flow is directed to the upstream particle counters. In a similar way, the air leaving the scavenging box will also be split into two fractions. The major fraction will be directly exhausted from the lab, while the remaining fraction is sent to the downstream particle counters. The upstream and downstream particle counters will measure DPM concentration (i.e., by particle number as a function of size) entering and exiting the scavenging box as can be seen in Figure 2.

For the initial project stages, the scavenging box will be constructed of clear plastic, and will include a water drain. The spray source (12 in Figure 2) will be an ultrasonic nebulizer which converts high frequency electrical energy to mechanical vibrations, which are intensified by a probe to break water into micro-droplets. A 40 kHz atomizing probe will be used, providing atomization rates up to 30 mL/min and a median drop size of about 50µm [34]. The atomizer will be mounted on the top of the scavenging box, and the water (15 in Figure 2) entering this equipment will be regulated with a peristaltic pump (14 in Figure 2).

Key to the lab setup are the particle counters (6 in Figure 2). The TSI 3910 nanoparticle counter (NanoScan) will cover the size range 0.001-0.45µm (10-450nm) while the TSI 3330 optical particle sizer (OPS) will cover the range 0.3-10µm [35, 36]. Two diffusion dryers (5 in Figure 2) will be used to ensure that the particle counters only count DPM (and not water droplets). These pieces of equipment dry and remove water vapor from the gas flow by collecting large water droplets at the inlet and removing excess moisture by diffusional capture [37]. A bypass line including a mass flowmeter (17 in Figure 2) with a filter upstream (16 in Figure 2) will be introduced into the piping design before the scavenging box exhaust (i.e., water spray treated air) is ducted out of the room. By having an accurate measure of the flow leaving the scavenging box, along with information about other flows in the system, an analytical balance should be possible.

The lab setup described here is currently under construction, and is expected to be completed by Fall 2015. At this time, work under Task 2 will begin. In the meantime, preliminary testing of specific components is underway.

4. Conclusions

DPM represents a serious concern for worker health in underground mines, and existing methods for ensuring that exposures are sufficiently limited may affect operational flexibility in many instances. Much work has been done to reduce DPM exposure by using a combination of administrative and engineering controls. However, the abatement of DPM is not trivial, and new technologies coupled with the existing methods are needed to optimize health protection and efficient operations. Water sprays, which have proven to be a useful tool in underground mining for the abatement of dust, represent a promising but scarcely studied engineering control. Evidence, including theory and some practical work in non-mining environments, suggests that a fraction of DPM might be scavenged by the use of water sprays.

Research conducted as part of a new Capacity Building in Ventilation project will provide fundamental insights into DPM-droplet interactions and specific conditions favoring the scavenging of certain DPM particle size ranges. This research will thus contribute to the scientific literature and address practical implications of water sprays as a novel DPM abatement technology in underground mine environments.

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