DPM Monitoring in Underground Metal/Nonmetal Mines

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The metal and nonmetal mining industries face increasingly stringent regulations regarding worker exposures to airborne particulates, including diesel particulate matter (DPM). Although significant progress has been achieved in reducing DPM exposures, mine operators still struggle to comply under a variety of conditions – particularly in large-opening mines where ventilation is challenging. One major issue in such environments is the inability to easily monitor DPM trends over long periods of time to determine factors influencing its buildup in areas of interest, as well as its response to mitigation strategies. At present, DPM measurements are limited to the NIOSH 5040 method (i.e., filter collection and external analysis) and the handheld Airtec DPM monitor (FLIR Systems, Inc., Albuquerque, NM), which provides quasi-real time data over relatively short time periods.

To transform the Airtec device to an autonomous area-monitoring unit, its basic components were modified by Nomadics, Inc. under NIOSH contract number 200-2010-36901. This resulted in a prototyped unit called the Airwatch DPM monitor, which does not require frequent filter replacement or battery re-charging; networking capabilities to connect multiple monitors were also achieved. While the prototyped monitor was successfully lab tested, field-testing was limited to just a few days underground. Further testing is needed to fully evaluate the monitor and ready it for commercial availability. Under a new Capacity Building in Ventilation project at Virginia Tech (CDC/NIOSH contract no. 200-2014-59646), we aim to demonstrate the capability of the Airwatch DPM monitor in high-priority areas of a stone mine over relatively long-term periods – and then use the monitors to investigate DPM response to ventilation conditions.

Keywords: Diesel Particular Matter, Metal/non-Metal, Monitoring

1. Introduction

Diesel exhaust represents a ubiquitous occupational hazard in underground mine environments. The exhaust is a highly complex mixture of diesel particulate matter (DPM) and hydrocarbon gasses [1]. Since there is no technologically proven way to measure DPM directly, it is often quantified using elemental carbon (EC) measurements. [2]. Elemental carbon accounts for 23-100% of DPM, and is not generally affected by environmental interferences [3,4]. Historically, total carbon (TC) analysis was used which typically comprises over 80% of DPM [1]. TC is defined as the summation of elemental carbon and organic carbon (OC). However, cigarette smoke and mineral dust can interfere with TC readings, which has sometimes caused DPM measurements to report artificially high values [3].

DPM has a variable particulate size distribution. Particles are created within the micron and sub-micron scales [5]. Idealized size distribution is trimodal and related lognormally [1]. The smallest particulate mode is called the nuclei mode, which has particles diameters ranging from about 0.005 to 0.05µm. This mode represents less than 20% of DPM by mass, but greater than 90% of DPM by particle count [1]. Most DPM particulate mass is represented in the accumulation mode, with particle diameters on the order of about 0.05 to 1.0µm. The coarse mode represents particles with diameters greater than 1µm. All particles sizes are capable of suspension in air, and DPM is prone to clustering and reacting with other atmospheric components while suspended [1]. Such reactions may create synergies that are harmful to human health. DPM exposure in U.S. underground mines is regulated by the Mine Safety and Health Administration (MSHA). MSHA issued its Final Rule on DPM metal and nonmetal mine environments under 30 CFR Part 57 in 2008, mandating that a miner's personal exposure limit (PEL) to DPM cannot exceed 160 $\mu g/m^3$ of TC during an eight-hour work shift. MSHA requires that the standard National Institute for Occupational Safety and Health (NIOSH) 5040 Method be used to measure DPM exposures to determine compliance [4]. This method employs a thermo-optical technique to analyze carbon particles in air samples collected on a 37 mm quartz fiber filter. It should be noted that this technique quantitates TC (by direct quantitation of EC and OC) or requires a site-specific conversion factor to convert EC into a TC equivalent [6,7]. These values should then be adjusted to an eight-hour time-weighted average.

1.1 DPM and Human Health

Underground miners are disproportionally exposed to DPM-related occupational hazards because heavy diesel-powered equipment runs regularly in tight spaces, with variable ventilation conditions. In spaces where airflow is limited, DPM does not disperse well, and due to its size can remain suspended in the air. Reported DPM concentrations in underground mine settings can be on the order of ten times higher than levels found in some other industrial settings, and more than 100 times higher than levels observed in urban areas [1]. NIOSH

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estimated in 2008 that 34,000 underground miners were at risk of exposure to DPM [1].Human exposure to DPM presents many potential health complications. NIOSH estimated in 2008 that 34,000 underground miners were at risk of exposure to DPM [1]. Approximately 60,000 deaths in the United States per year are attributed to fine particulate exposure. Of these deaths, 21,000 are believed to be from DPM in particular [5]. The Clean Air Task Force reports that the estimated annual economic cost of particulate-related illness and death in the USA was $139 billion [8]. Clearly, the social and economic impact caused by particulate-related illnesses should not go unaddressed.

2. DPM Monitoring

As noted above, for demonstrating compliance with DPM exposure limits in underground metal and nonmetal mines, the NIOSH 5040 method must be used. While this method provides an accurate measurement of EC and OC concentrations (which can be translated into TC as proxy for DPM) over the short duration of sample collection, it is intended for determining personal exposures. Thus, it does not provide the ability to easily monitor DPM over long periods of time. For understanding DPM trends in the context of mine operation, and therefore mitigating exposure risks, monitoring capabilities are indeed critical. Recognizing this fact, a handheld, quasi real-time DPM monitor called the Airtec (FLIR Systems, Inc., Albuquerque, NM) was developed in collaboration with NIOSH. The Airtec is now commercially available as an engineering tool for mine operators. Another device, the Airwatch, has recently been prototyped. It is intended to meet the need for autonomous area monitoring, but is not yet ready for commercialization.

The following sections describe these three DPM monitoring options for underground metal and nonmetal mines, and their key characteristics are summarized in Table 1.

2.1 NIOSH 5040 Method

The most up to date version of the NIOSH 5040 method was published in 2003 [6]. The method incorporates thermo-optical analysis because of its selectivity and flexibility (e.g. can run manually and is programmable). The instrument was specifically developed for analysis of carbon-based aerosols (e.g., DPM) and is manufactured by Sunset Laboratories, Inc. (Tigard, OR). In general, the thermal analysis is completed in two phases. First, the sample is placed in an oven and heated to 850°C in inert atmosphere, causing the OC to become catalytically oxidized. This forms carbon dioxide, which can then be reduced to methane. The methane is then measured using a flame ionization detector (FID) [9]. Next, the sample is re-heated up to about 900°C in an oxygen-rich atmosphere, such that the EC is also oxidized; again, the resulting carbon dioxide is reduced to methane, which is measured by FID. Since some char is produced by the OC during the first phase, which will oxidize in the second phase, the analyzer must also determine how much methane in the second phase is attributable to OC vs. EC. For this, it contains a pulsed diode laser and photodetector to monitor the sample for transmission of light. Effectively, once the transmittance is seen to increase (i.e., char production in first phase) and then decrease back to its original value (i.e., char oxidation in the second phase), all subsequent methane production is attributed to EC. For this optical analysis, the instrument requires a portion of the sample filter wider than the diameter of the laser [10,11].

To collect DPM samples for analysis by the 5040 method, a field sampling apparatus is used which consists of a small air pump, and a 37 mm quartz fiber filter that is held inside a plastic cassette. Often a device for removing relatively large particles from the DPM-laden airflow is also placed inline before the sample filter; generally, the oversized particles (i.e., > 0.8μm) are removed via an impactor filter. By using a size-selective sampler, airborne dust (i.e., which may include carbon-containing particles) is prevented from collecting on the DPM filter and creating a sample matrix interference for the analytical method [2]. When the impactor becomes full, DPM capture is no longer efficient and the impactor must be replaced. SKC manufactures an all-in-one DPM cassette, which contains an impactor and quartz fiber DPM filter [12]. In very dusty environments, a cyclone may also be placed inline before the sampling cassette to exclude relatively large (i.e., > 5μm) particles before air reaches the impactor.

In an earlier design, the SKC DPM cassette was observed by Noll et al. to be problematic [2]. Specifically, DPM deposition on the filters was not uniform in regards to the surface area (i.e., surface areas over which DPM deposited were irregular and varied between cassettes.) Uniform deposition is critical for accurate calculation of aerosol EC, and then TC, concentrations since only a fraction of the filter is analyzed and must be assumed representative: the 5040-quantitated EC and TC masses are effectively converted to concentration values based on the fraction of sample surface area analyzed, the sampling time and the flowrate [2]. Once modification was made to improve the cassette design, they were determined to provide reliable measurements in laboratory and field environments [2].

Following promulgation of DPM rules in underground mines, the NIOSH 5040 method has provided a means for gathering a wealth of information, particularly about personal exposures; and improvements in the mine environment have undoubtedly resulted. However, this method, it is not a particularly practical engineering tool for mine operators aiming to conduct routine monitoring of DPM. Collected samples must be mailed to only a handful of equipped laboratories to perform the required analysis, which makes collecting results quite time consuming [5] – not to mention expensive. One test costs approximately $100 for supplies and analysis, and this figure does not include mine labor [5]. Moreover, the lag period between sample collection and analysis makes it difficult to both recognize the conditions leading to overexposures and to gage the effectiveness of attempted DPM control mechanisms.

Beyond the issue with significant lag time between sample collection and result reporting, 5040 method results are also limited because they are associated with bulk samples (i.e., the final result is a time-weighted average concentration). This means that particular time segments within the sampling period cannot be isolated [5]. It would be helpful for mine operators to determine when peak exposures of DPM occur, ideally in real time, so that they can adjust ventilation controls accordingly.

2.2 In-mine DPM Monitoring

To address the need for in-mine monitoring, the Airtec DPM Monitor was developed. It is a handheld device and displays EC concentrations on a running 15-minute average – quasi real-time. The instrument meets NIOSH accuracy criteria and provides results with no statistical difference from the 5040 method [13]. It measures EC using a laser extinction technique, which works because EC concentrations are related to laser absorption [13]. The laser extinction is measured directly on a filter as it collects DPM, which is ideal for a small, portable device.

Mine operators may use the Airtec to "spot" check areas of interest in order to identify high DPM contributing sources, and also to evaluate personal exposures to DPM. It has proven particularly useful for monitoring DPM in equipment cabs because it is not influenced by instantaneous pressure changes, such as those caused by opening and closing doors [7]. Researchers at NIOSH have observed that the Airtec is sensitive to cigarette smoke and will register it as a DPM reading [7], and so users should be aware of this potential for false-positive readings and not smoke while the monitor is being used. Being able to monitor DPM in near real-time allows mine operators to identify when levels are nearing compliance limits, as well as evaluate the effectiveness of engineering controls to abate it.

Functionally, the Airtec monitor has three main parts: a small air pump, a plastic cassette that holds a filter onto which DPM is collected, and a laser and sensor pair. As the DPM is collected, the laser is directed toward the filter and the sensor detects how much of the laser becomes blocked by EC (a primary component of DPM). The laser becomes increasingly "extinct" as more DPM is collected, and thus an effective measurement of EC is obtained. As is often the case with filter samples collected for the 5040 method, the Airtec can also use an impactor to keep dust from entering the device and depositing on the filter. (Previously, a "sharp cut" cyclone was also commercially available that could effectively remove particles > 0.8μm, but this model of cyclone is not being manufactured anymore.)

While the Airtec has afforded significant monitoring capabilities to mine operators, a new device developed under NIOSH contract number 200-2010-36901 called the Airwatch DPM Monitor may provide even more utility in the way of long-term area monitoring. The Airwatch is currently in the prototype and demonstration phases. It is technologically similar to the Airtec, but includes several modifications that allow the device to operate autonomously over long periods of time. Most importantly, it can run on mine power (i.e., instead of batteries) and does not require frequent user attention or maintenance. The latter is possible because the Airwatch uses a self-advancing filter tape on which the DPM is collected [14]. The tape is similar in form to an audio or VHS cassette tape, wherein the clean filter media is rolled around one cylinder from one end and attached to another cylinder on the other end. DPM is collected via an air pump and deposited on a small area of tape between the two cylinders. Here, a laser and sensor pair similar to those used in the Airtec units is employed to track laser extinction, which can again be related to EC collected on the filter tape. When a given filter area is completely used (i.e., laser extinction is sufficiently high), the tape progresses forward to expose a clean area of filter to the laser and sensor. The exact life of this filter tape depends on the sampling environment and monitoring setup (i.e., concentration of DPM in the air, and frequency at which the Airwatch is programmed to collect data.) To avoid interference in laser extinction from dust particles, a sharp-cut cyclone is employed to prevent dust particles from depositing on the filter. As opposed to an impactor for this purpose, the cyclone does not need frequent replacement

Table 1. DPM Monitoring Options

Method	Analytical Technique	Primary Applications	Availability of Results	Sampling Unit
5040 Method	Thermo-optical with FID (quantitates EC and OC)	Personal exposures (required for compliance), short-term area monitoring	Lag time (days to weeks)	Portable
Airtec Monitor	Laser extinction (quantitates EC)	Personal exposures, short-term area monitoring, spot-checking	Quasi real-time	Portable
Airwatch Monitor	Laser extinction (quantitates EC)	Long-term, autonomous area monitoring, networking capabilities	Quasi real-time	Stationary

In its current design, the Airwatch can be programmed to transmit data to remote monitoring cations via hardwires (i.e., Ethernet or 4-20mA). Since a current-based signal is used, the signal transmitted does not degrade over distance. Where available, mining operations could certainly benefit from real-time DPM information that can be transferred quickly over wireless networks, and this capability is also envisioned for the Airwatch monitor. Long-term, operators might be able to centrally process data and automatically incorporate them into other systems or decision-making schemes to alter mine parameters, such as ventilation [15]. Although the Airwatch has been successfully tested in the laboratory, extensive field testing has not been conducted to date

3. Research Approach

Under a new Capacity Building in Ventilation project sponsored by CDC/NIOSH through the Office of Mine Safety and Health Research (contract no. 200-2014-59646), the Airwatch technology will be demonstrated in an underground mining environment, and ultimately employed to monitor DPM under different ventilation scenarios.

The focus environment for this project is the large-opening mine. These mines experience airflow quantities so low that they are sometimes immeasurable with conventional equipment. In many, ventilation techniques are currently being employed to control DPM but they are still highly experimental, using trial-and-error approaches to gage effectiveness [16]. These are notably costly, time-consuming, and less than optimal in terms of DPM control – certainly far from ideal. Some mines do not even have forced-ventilation systems in place. Rather, they depend on natural ventilation, which is uncontrolled and unreliable due to seasonal variations in temperatures that drive the movement of air [16]. Only a few research studies have been conducted regarding DPM in large-opening mines (e.g., see 16-18), but it is clear that effective, data-driven ventilation improvements require enhanced DPM monitoring networks.

3.1 Project and Task Description

Two main objectives related to DPM monitoring and ventilation have been established for this project: 1) to demonstrate the capability of the prototyped Airwatch devices to autonomously monitor DPM in high-priority areas of a study mine and 2) to determine DPM response to ventilation conditions in various areas of the mine. Work began during late 2014 and will be developed over the remainder of the five-year project. Table 2 displays the tasks that will be undertaken in order to fulfill the project objectives.

3.3 Progress to Date

Work is proceeding in cooperation with an industry partner (an underground stone mine) and to date, there has been progress towards Tasks 1 and 2. For Task 1, due to the very low air velocities in the study mine, it will be necessary to use an ultrasonic anemometer to collect accurate data. A UA6 (TSI Incorporated, Shoreview, MN) is currently being lab-tested and will be employed for spot ventilation surveys. The ventilation data will be collected in concert with DPM data using the Airtec monitor. Survey points will be chosen together with the mine operator. A customized DPM cassette, designed and 3D-printed by NIOSH, will be used to reduce the DPM deposition area on the filters. This will effectively reduce the total surface area of the DPM filter so that the Airtec unit is much more sensitive and can provide faster EC readings (versus the 15-minute minimum sampling time that is normally required).

For Task 2, upgraded Airwatch monitors have been built (on a separate NIOSH contract). The new units have been modified to make them more rugged and user friendly. Comparative measurements are planned whereby the Airwatch and Airtec units will be employed simultaneously. Moreover, work is currently underway to design self-contained monitoring stations that couple a 2-axis ultrasonic anemometer that logs data cooperatively with an Airwatch unit to track air velocity. This future work will help determine how DPM responds to ventilation controls. Due to environmental conditions, the datalogger should be stowed inside some type of moisture-proof enclosure to protect it from atmospheric conditions.

4. Impact

Despite significant improvements over the past couple of decades, DPM is still a significant health concern for underground mine workers. Efforts to further reduce exposure risks require enhanced monitoring tools. Demonstration of the efficacy and utility of the Airwatch DPM monitor is expected to aid in progress toward its commercial availability. Ultimately, this tool should provide mine operators a means of tracking DPM with other environmental and operational conditions (e.g., ventilation) such that worker health can be adequately protected while optimizing other factors (e.g., energy usage, production, maintenance schedules, etc.).

Beyond theses expected research outcomes of the Capacity Building in Ventilation project described here, development of expertise in the areas of mining engineering and occupational health is a primary objective. The project team includes multiple student researchers. Their current work will add to the scientific literature surrounding DPM monitoring and control; and the knowledge and experience they gain during this project will soon contribute to the broader mining community.

Table 2: Work tasks related to DPM monitoring and ventilation response

Task	Description

Initial Collection of Mine data (Year 1)	• Become familiar with operation and environmental conditions at the mine of study.
	• Conduct ventilation and DPM surveys by using:
	  o Airtec real Time Monitors
	  o Ultrasonic Anemometers

Receipt and lab resting of prototyped autonomous DPM monitors (Years 1-2)	• Receipt of prototyped autonomous DPM monitoring units from NIOSH
	• Becoming familiar with the units' design and operational requirements.
	• Units will be lab tested to confirm they are functioning properly
	  o Capability to measure continually
	  o Capability to log data
	  o Accuracy and consistency amongst all units output.
	• Verification of autonomous DPM monitors' readiness for use underground.

Field-testing of autonomous DPM monitors (Years 2-4)	• Determining installation locations together with the mine operator.
	  o High priority areas for monitoring of DPM
	  o Safe and reliable for the operation of the testing equipment.
	• Installation of the prototyped monitors at the field site
	• Ensuring proper functioning in the mine environment and capability to record DPM data for long periods of time

Monitoring DPM responses to specific ventilation (Years 4-5)	• Tracking DPM response to different ventilation scenarios. • Scenarios will be determined in conjunction with the mine operator

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