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Field Evaluation of Diesel Particulate Matter Using Portable Elemental Carbon Monitors

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ABSTRACT: Regulations on worker exposure to diesel particulate matter (DPM) are becoming increasingly stringent in the mining industry. Due to the complexity and unpredictability of this aerosol, there is a need for new tools to help mines develop an effective strategy to reduce DPM concentrations. To address these needs, NIOSH has developed a portable elemental carbon monitoring device for use in underground mines. These instruments are compact and capable of measuring elemental carbon concentrations in real time. The information that they provide is useful when planning new DPM curtailment strategies or when measuring the effectiveness of existing DPM controls. The following paper discusses a variety of ways that these instruments have been used to help lower DPM concentrations and exposure to DPM in active mines.

1 Introduction

In May, 2008, the Mine Safety and Health Administration significantly lowered the permissible exposure limit of underground mine workers in the U.S. to diesel particulate matter (DPM). The new regulation states that “a miner’s personal exposure to diesel particulate matter in an underground mine must not exceed an average eight-hour equivalent full shift airborne concentration of 160 micrograms of total carbon per cubic meter of air (160 TC ug/m^3)”, where TC is the sum of elemental carbon (EC) and organic carbon (OC) (MSHA, 2005). This adjustment is a substantial reduction from the 2007 interim limit of 350 TC ug/m^3.

In order to comply with this regulation, most mines must employ one, or a number of combined control strategies in order to lower DPM concentrations. Some options available to mines include: improved vehicle maintenance programs, increased or re-routed ventilation, upgrading fleet to newer engines, use of alternative fuels such as biodiesel, the addition of diesel particulate filters (DPFs) to key vehicles, changes to truck traffic and other administrative controls. Because these strategies vary greatly in the amount of reductions attainable and the costs of implementation, it is important to have a thorough understanding of the DPM emissions within the mine so that the most effective control strategy can be utilized. In the past, obtaining a clear understanding of DPM sources and transients throughout a mine would have been almost impossible, but recent advancements in DPM measurement techniques have made this more feasible.

1.1 Real-time Monitoring

The traditional method for measuring DPM in underground mines is based on the NIOSH 5040 method. Although this procedure may be the most accurate method for collecting and measuring compliance samples of DPM, the time and cost involved in the process make it an impractical method for mines that are looking to monitor the effectiveness of DPM controls. In addition, the NIOSH 5040 method is a one-dimensional measurement, meaning that it simply provides an average DPM exposure measurement over a given time period without recording critical information pertaining to the cause of the overexposure. Because of these pitfalls, NIOSH has developed a portable instrument that is capable of measuring concentrations of elemental carbon (EC) in near real-time (hereby referred to as “DPM monitors”). Using EC as a surrogate for TC, these instruments can provide DPM measurements quickly and continuously in an underground mine. In addition, they also provide charted outputs of DPM concentration changes over time. Because these concentrations are often transient in nature, understanding this data will help mine operators obtain a clearer picture of how DPM levels are affected by mining activity and how well they respond to control strategies. This data can provide valuable information on the effectiveness of ventilation, vehicle-specific emissions, DPF failures, miner-specific exposures, and the effectiveness of cab filtration systems. The following is a discussion on how real-time monitoring technology can be used to evaluate DPM problem areas and aid in the selection of effective DPM control strategies.

1.2 Capabilities, Limitations and Interferences

The instruments used for real-time measurement of DPM are beta prototypes supplied by ICx technologies. These portable devices rely on a rolling average to measure DPM levels. Therefore, when used as an area sampler or a personal sampler, they provide a measurement of the average concentrations of DPM over the previous five, ten and fifteen minutes as well as the time-weighted average exposure measurement (TWA) for an eight hour shift. All of these measurements are updated once per minute. The lower limits of quantification of the instrument are as follows; 18 ug/m^3 EC for TWA, 110 ug/m^3 EC for five minute rolling averages, 62 ug/m^3 EC for ten minute rolling averages, and 54 ug/m^3 EC for fifteen minute rolling averages (Janisko et al., 2008).

As with most technologies, the information that the DPM monitors provide is subject to certain limitations and interferences. Although these limitations are minor compared to the value of real-time analysis, it is important that users are aware of this information when employing these devices.

The monitors use EC as a surrogate to measure DPM. This means that, in countries without an EC standard (such as the United States), an EC to TC ratio must be set on the instrument in order to convert EC measurements to TC. This ratio can vary from mine to mine, and is best obtained through the collection and analysis of a large number of 5040 samples (Noll et al., 2007). Many mines may already have this information from previous analyses. For compliance sampling, MSHA requires that both the direct measurement of TC and the surrogate measurement of TC (using an EC/TC conversion factor obtained from an area sample collected in the main exhaust and downstream of the miner in question) be under the 160 ug/m^3 personal exposure limit (MSHA, 2008).

When used as directed, dust will not interfere with the monitor's reading in metal/non-metal mines. However, when the monitors are exposed to drastic changes in temperature from cold to hot, condensation can build up on the sampling cassette within the instrument and cause false overestimations of DPM concentration. This interference has been seen primarily in cold climates and lasts for only a short duration. Typically, it occurs when traveling from a warm section of the mine to the intake. After a short time, the system will equilibrate and the monitor will begin functioning properly. This interference is recognizable in the data as large abnormal spikes that correlate with times when the monitor was exposed to drastic changes in temperature (07:50-08:15 of Figure 1). Another method for detecting this interference is to analyze a chart of the sensor output throughout a test. Under normal conditions, the sensor voltage will decrease or remain constant throughout the testing period. If the signal ever rises (as it does around 08:07-08:15 of Figure 2), this is a good indicator that a temperature interference has occurred. In Figure 1, the data before and after the interference would still be accurate.

This effect also needs to be accounted for when using the monitors to measure tailpipe emissions. In these cases, exhaust gas should be cooled and water should be removed before entering the sampling stream of the instrument.

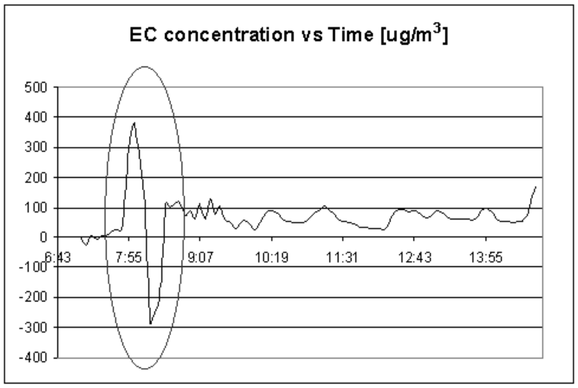

Figure 1 A chart of EC concentration vs. time, showing temperature interference at 07:50-08:15.

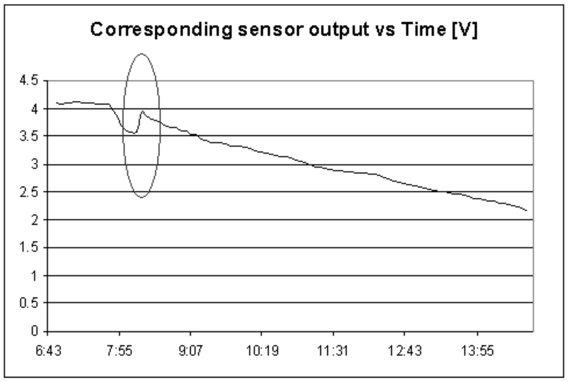

Figure 2 A corresponding chart of sensor output showing an increase in signal at 08:07.

2 Methodology and Results

2.1 Sampling Techniques

The following tests were performed at active mines. Depending on the nature of the test, measurements of DPM concentration were either read directly from an LCD screen on the instrument at the time of testing or downloaded from the internal memory of the instrument after the testing period.

2.2 Measuring the Effectiveness of Ventilation in an Area

Adjusting the mine's ventilation system can be one of the easier and more cost effective solutions when combating DPM emissions. However, it is important to understand how successful these ventilation increases will be before committing to this control strategy. The DPM monitors can be used to measure the adequacy of ventilation in an area (in terms of DPM flushing) and to estimate the point at which further increases become inefficient when weighed against the increased cost and complexity of such a solution.

Figures 3 and 4 show data that was collected in two active metal/non-metal mines in 2009. In the first case, measurements were taken at the main exhaust for approximately six hours. The monitor was left unattended during the test period. As shown, the concentration of

DPM built slowly, but steadily, throughout the test. This is a “fingerprint” trend which indicates that a ventilation increase might be successful at lowering DPM concentrations.

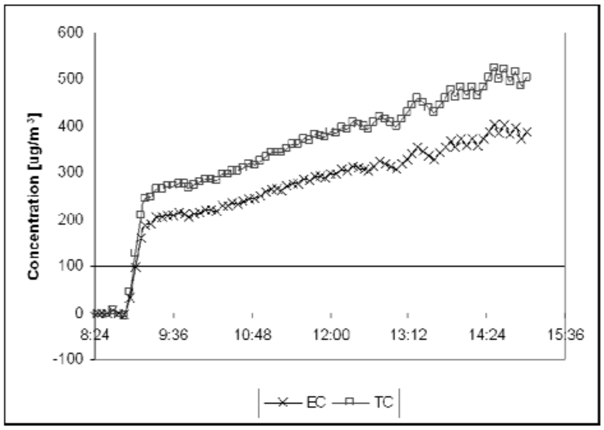

Figure 3 A chart showing a steady increase in EC and TC concentrations from 200 to 400 ug/m^3 and 250 to 500 ug/m^3, respectively, throughout a six hour time frame.

Often times, attaching the DPM monitors to the exterior of a vehicle is a superior method of collecting data in an area because measurements can be taken near the center of the entry and directly within the working zone. Figure 4 shows a case where area measurements were collected on a mucker during its working cycle. Although these measurements are more prone to fluctuation from localized activity, a similar trend can still be found in the data (Figure 4).

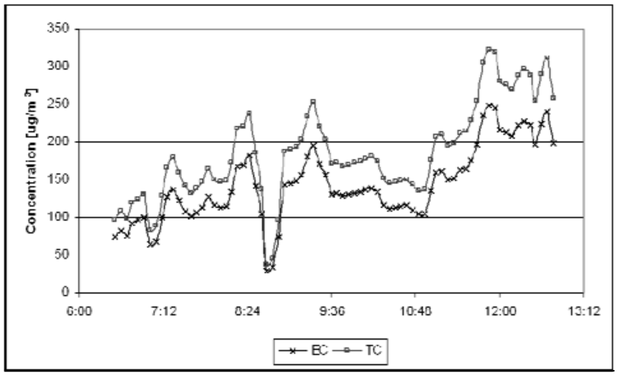

Figure 4 A chart showing a fluctuating, but overall increase in EC and TC concentrations from 75 to 200 ug/m^3 and 100 to 260 ug/m^3, respectively, throughout a six hour time frame.

Both of these examples highlight the advantages of real-time measurement and full-shift sampling when analyzing DPM conditions in an area. Without a comprehensive measurement, increases in DPM concentrations throughout the shift may have gone undetected.

Although not available at the time, a good method for measuring the effectiveness of ventilation changes to that area would be to increase the air flow to that section of the mine without changing any other parameters that would influence DPM concentration levels (truck traffic, changes in work flow, etc.). From this, a grasp on how much air-flow equals a particular reduction in DPM concentration could be derived.

2.3 Measuring Vehicle-specific Contributions to DPM

When choosing a DPM reduction solution, it is often assumed that diesel particulate filters are the preferred method for controlling particulate emissions. Although these filters have shown the potential to drastically reduce DPM emissions (Bugarski et al., 2007, McGinn et al., 2002), they can present additional up-front costs and maintenance demands (EPA, 2007) as well as concerns over increased NO_2 emissions in catalyzed systems (Czerwinski et al., 2007, Mogenson et al., 2009). For these reasons, it is not uncommon to find cases where it would be more efficient to single out the major contributors to DPM emissions within a mine’s fleet and outfit those vehicles with particulate filters while attacking the rest of the fleet with other methods such as enhanced maintenance programs, administrative controls or alternative fuel blends. In these cases, it would be beneficial to know the individual contributions of particular vehicles to total DPM emissions throughout the mine (i.e., the vehicle-specific emissions) so that the most effective plan could be developed.

2.3.1 *Isolated zone testing for vehicle-specific emissions*

The best technique available for measuring vehicle-specific DPM contributions is an isolated zone analysis. When performing these tests, a vehicle is operated in an inactive section of the mine which is as free from DPM interference as possible (i.e. the isolated zone) (McGinn et al., 2002, Bugarski et al., 2005, Bugarski et al., 2006). The goal is to mimic the typical loading cycle of that engine under normal operating conditions. This is accomplished by running the machine through a simulation of its working cycle within the isolated zone throughout the length of the testing period. The benefit of this type of analysis is that it more closely replicates engine transients than other forms of vehicle-specific testing. The primary limiting factors are the ability to maintain prevailing ventilation conditions and accurately simulate working cycles. For a detailed description of isolated zone methodology, the reader is referred to: “Performance Evaluation of Diesel Particulate Filter Technology in the Underground Environment”, McGinn et al., 2002, and “Evaluation of Diesel Particulate Filter Systems and Biodiesel Blends in an Underground Mine”, Bugarski et al., 2005.

Figure 5 shows real-time measurements that were taken during an isolated zone test in a metal mine in 2009. In this experiment, a mucker was operated within the isolated zone, moving ore with the air flow, from the upstream end to the downstream end in a continuous cycle. Two breaks in testing occurred at 11:32 and 13:47. DPM monitors were placed both upstream and downstream of the isolated zone to record changes in concentration throughout the test. In this case, because the entry was not much larger than the vehicle itself, the vehicle acted like a piston within the isolated zone –flushing DPM downstream when traveling downwind and partially pulling DPM against the ventilation when traveling upwind. This type of cycling can be observed in figure 5, although the data shows some clipping due to the response times of the monitors.

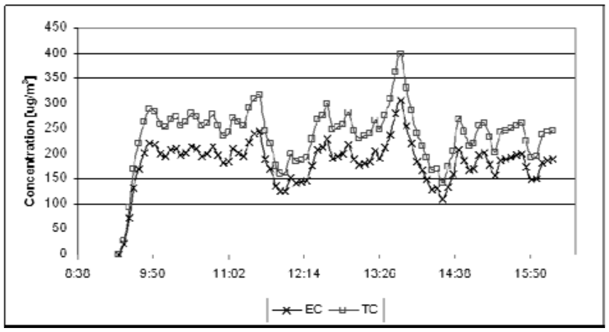

Figure 5 Real-Time measurements of EC and TC taken downstream during an isolated zone test. The chart shows concentration oscillations ascribed to the movement of the vehicle throughout the test.

In this case, the DPM monitor measured an average concentration of 180 ug/m^3 EC at the prevailing ventilation rate and a time-weighted average of 172 ug/m^3 EC over the testing period. The upstream measurements were below the limits of quantification of the instrument, and were therefore not corrected for.

In order to make use of this data, the other vehicles in the fleet should be analyzed in a similar manner, and the contributions to DPM emissions compared proportionally. The time that a particular engine spends within the mine during a given shift and its location(s) as well as instances when the vehicle is idling all need to be factored into this analysis. Once this process is completed, vehicle emissions can be combated on a priority basis, reducing costs and enhancing the effectiveness of the chosen DPM control strategies.

The real-time monitors make it possible to perform isolated zone tests more easily than in the past. Because instantaneous results are available, it is possible to perform tests on multiple vehicles on the same day as well as quickly recognize when tests have been compromised. These benefits make a comprehensive analysis of the vehicle-specific emissions of a mine’s fleet more feasible than in the past.

2.3.2 *Tailpipe monitoring for vehicle-specific emissions*

Another method that has been used to measure vehicle-specific emissions with the DPM monitors is direct tailpipe sampling. In this type of testing, engines are tested at three different modes; idle, high idle and torque converter stall. A unique sampling probe that cools the exhaust and removes water is attached to the inlet of the monitor. Measurements are taken for 30 seconds to two minutes, depending on the “cleanliness” of the exhaust. The output of the sensor within the instrument (voltage) is recorded before and after sampling. The percentage decrease is then correlated to DPM concentration through calibration data.

Although still under development, this method has shown promising results in initial testing. The benefits of this method are that it is free from outside sources of DPM interference, easy to perform and highly repeatable. One drawback of this method is that it is performed at arbitrary engine conditions (under non-transient loads) and is therefore difficult to correlate with actual vehicle-specific emissions during a production shift. In addition, this method does not account for leaks within the exhaust system of the vehicle, and is therefore best utilized as an accompaniment to isolated zone testing (McGinn et al., 2002).

2.3.3 *Area sampling for vehicle-specific emissions*

A third, and fairly crude method for measuring vehicle specific contributions using the DPM monitors is to select a strategic location for area sampling throughout a shift and measure the fluctuations in real-time concentration over time. Matching the time-stamped data from the monitors with the times when an individual vehicle has passed the sampling location can provide a basic look at which vehicles are the largest emitters in that area of the mine. Although easier to perform than an isolated zone study, in terms of vehicle-specific emissions, this method is only useful to identify which vehicles are the major emitters of DPM in that area and is not practical for quantifying individual vehicle contributions.

2.4 Measuring the Effectiveness of Diesel Particulate Filters

The efficiency of diesel particulate filters (DPFs) is measured by evaluating the DPM concentration within an exhaust system before and after the filter (McGinn et al., 2002). This method is simple and unbiased, but requires well-controlled testing and laboratory-grade instrumentation. In practice, it is very difficult to quantify the efficiency of on-board DPFs with real-time instrumentation in an underground environment. This is due to the lack of field–worthy instruments that are capable of measuring the low concentrations typically found in filtered exhaust. NIOSH is currently investigating the possibility of a retrofit technology which may make the DPM monitors able to achieve this. In the interim, the monitors can be used to detect instances of DPF failures as well as to measure the extent of the malfunction.

Using the tailpipe measurement procedures outlined in section 2.3.2, the engine should be forced into a high load mode (such as torque converter stall). A five minute measurement should be taken at the end of the tailpipe (downstream of the filter) and the initial and final sensor readings on the instrument should be recorded.

In a properly functioning system, this reading should not drop significantly. However, if this measurement decreases by more than 5% from its initial value, then the instrument has detected above its limit of quantification and, in theory, an approximate filtration efficiency can be obtained. To do this, an identical measurement should be taken from upstream of the DPF. The two measurements can then be plugged into equation (1):

$$\text{approx. \% efficiency} = 100 * \left(\frac{\log\left(\frac{V_{\text{upstream,final}}}{V_{\text{upstream,initial}}}\right)}{\log\left(\frac{V_{\text{downstream,final}}}{V_{\text{downstream,initial}}}\right)} \right) \qquad (1)$$

Since tailpipe measurement with the DPM monitors is a relatively new technique, the approximated efficiency should be used to monitor changes in the consistency of DPF filtration over time rather than as a comparison against manufacturers' predicted efficiencies. If, in any of the measurements, the signal increases back near the original value after the probe has been removed, then condensation has interfered with the measurement and the test should be repeated (see 1.2 Capabilities, Limitations and Interferences).

Because of the increased back pressures that are common with many DPF systems, leaks can significantly affect efficiency measurements. Therefore, any measurement of filtration effectiveness remains uncertain without an accompanying ambient measurement to validate the integrity of the plumbing.

2.5 Measuring Miner-specific Exposure to DPM

For compliance sampling, MSHA requires that a shift-weighted measurement of EC and TC exposure be taken (via the NIOSH 5040 method) from a mineworker's breathing zone. To do this, a mine worker is outfitted with a sampling train consisting of a pump, flexible tubing and an integrated cyclone/impactor/filter assembly. The DPM monitors were designed to mimic this system and therefore use many of the same components.

The monitors are capable of providing both shift-weighted EC and calculated TC exposures in real-time and, in addition, can monitor changes in EC exposures throughout the entire shift. In some cases, it may be useful to ask the mineworker to record events that might affect DPM readings, such as times when the instrument was removed or unexpected changes in location. Coupling these records with the real-time measurements of EC and information on affective factors such as truck traffic, working conditions and ventilation rates can be useful when trying to pinpoint the cause of overexposures during a working shift. It is often the case that administrative controls can be implemented to limit these overexposures to DPM.

2.6 Measuring the Effectiveness of Cab Filtration Systems

Environmental cabs can be an effective means for limiting mineworker exposure to DPM. However, simply leaving the window open or periodically opening the door can introduce enough DPM into the cab to cause an overexposure. Placing DPM monitors on the inside and outside of a cab throughout a shift can provide easy measurement of the effectiveness of the cab filtration system.

In a previous study (Noll et. al, 2007), it was shown that this method can identify situations when a cab filtration system has failed, as well as identify occurrences where open windows or open doors are causing avoidable overexposures. In a properly functioning system, the monitor within the cab will measure only small concentrations of DPM throughout the shift, regardless of the exterior concentrations. An open door is characterized by a large spike in concentration that gradually falls to near-zero as DPM is flushed from the cab over time. A prolonged increase in DPM concentration within the cab that matches the exterior measurements is associated with instances where the cab window was left open. In some cases, simple administrative controls are all that are needed to remove these hazardous situations.

3 Conclusion

This paper provides a practical approach to using real-time DPM measurement for selection and evaluation of effective DPM controls. The ability to perform well-executed tests and to interpret the information that real-time monitors provide is an essential part of sophisticated DPM measurement.

In particular, the information provided in charts of concentration changes over time is of great value. This data offers a novel way of understanding the factors that influence DPM exposure and drive concentration transients in an underground environment. In addition, it provides mine operators with a legitimate resource to aid in the reduction of DPM concentrations to the U.S. MSHA 2008 exposure limit of 160 ug/m^3 TC.

It is the expectation of the authors that, as with all new technologies, a number of uses for these instruments have yet to be conceptualized. Therefore, the methods outlined in this paper should not be considered a comprehensive list, but rather as an initial guide to a number of exciting techniques for measuring DPM in an underground environment.

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