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Instrumentation for diesel particulate matter emissions research

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ABSTRACT: Measurement and sampling of diesel particulate matter in mine air presents a challenge due to the complexity of the diesel aerosol. The results of a series of tests carried out by the National Institute for Occupation Safety and Health, Pittsburgh Research Laboratory, in an underground mine were used to evaluate several measurement methods that are currently used to characterize particulate matter emitted by diesel-powered equipment. This paper presents an overview of these techniques and examples of the results along with a discussion of the advantages and information gained by each technique. The measurement methods discussed include particle size measurements using a scanning mobility particle sizer, total particulate matter measurements using a tapered elemental oscillating microbalance, a size selective sampling method for workplace and personal exposure assessment and a size-selective high volume sampling method for carbon analysis.

1 INTRODUCTION

Measurement and sampling of diesel particulate matter (DPM) presents a challenge due to the complex nature of diesel aerosols. There are a number of methods for DPM measurements and each method's relevance is dependent upon the information required. For instance, the Environmental Protection Agency (EPA) defines DPM as the mass of material collected on a filter at a temperature of 52°C or less after dilution of exhaust with air (EPA, 2002). The EPA is interested in defining the concentrations of DPM in ambient air. The Mine Safety and Health Administration (MSHA) currently regulates (MSHA 2005) the exposure of underground metal/nonmetal miners to DPM (MSHA, 2005) based upon the mass based concentration of elemental carbon (EC). EC was found to be a suitable surrogate for DPM in underground metal/nonmetal mines, since diesel engines are practically the only source of submicron EC particles in this occupational environment (MSHA, 2005). Other measurement methods for DPM in occupational environments have also included, respirable particulates ($<3.5\,\mu m$), smoking corrected respirable particulates and combustible respirable particulates among other methods (EPA, 2002).

The mass measurement methods discussed above all collect the DPM on a filter, which is then sent to a laboratory for mass determination. There are also methods available for almost real-time DPM measurements. Jimriska et al. (2004) used a tapered element oscillating microbalance (TEOM) to continuously measure $PM_{2.5}$during a study of diesel bus emissions. In this same study, a scanning mobility particle sizer (SMPS) was also used to measure semicontinuous size distribution and particle number concentration of the DPM. Kittleson (2004) used a photoemission aerosol sensor (PAS) to measure diesel particulate emissions. These measurements were made when the engine was operated at five steady-state conditions. The author compared the PAS measurements with results from a SMPS, a diffusion charger and a condensation particle counter.

In this paper, the results of a series of comprehensive tests carried out by the National Institute for Occupation Safety and Health, Pittsburgh Research Laboratory, in an isolated zone of an underground metal/nonmetal mine, will be used to evaluate several sampling and measurement methods that are able to characterize particulate matter emitted by diesel-powered equipment. The results from measurements using a SMPS, and TEOM as well as results from a high volume and low volume filter method will be discussed and compared.

2 METHODOLOGY

These tests were conducted in an isolated zone, a long underground mine entry ventilated by fresh air (see Figure 1). Isolated zone tests were designed to be a compromise between the genuineness of in-situ measurements of concentrations and the repeatability and accuracy of the emission measurements obtained under research laboratory conditions. These tests allowed the operation of vehicles under conditions and

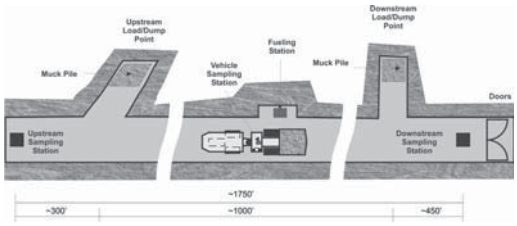

Figure 1. Isolated zone.

over duty cycles that closely mimic actual production duty cycles in an area that was not contaminated by emissions from other vehicles as would occur in tests conducted in real production areas. In addition, artifacts usually generated under laboratory conditions while attempting to simulate real-life conditions and processes do not compromise the results of isolated zone tests. A detailed description of the isolated zone methodology can be found in Bugarski et al. (2006a and 2006b).

Simultaneous measurements using each of the sampling methodologies described above were used to measure DPM concentrations downstream of the isolated zone (see Figure 1) as the vehicle was operated over a simulated duty cycle between the two load/dump points. The results obtained from tests conducted for two types of control technologies, water-fuel emulsions and diesel particulate filters, were used for this analysis.

3 INSTRUMENTATION

A description of various methods used in this study to collect particulate samples and directly measure concentrations of particulates is given below.

3.1 *Standard sampling of DPM for carbon analysis*

A standard sampling method (SSM) similar to the one used by the Mine Safety and Health Administration (MSHA) for DPM compliance monitoring [MSHA 2005] was used to collect DPM samples for carbon analysis. All samples were collected in triplicate.

The standard sampling method uses a sampling train consisting of a flow controlled pump, a 10 mm Dorr-Oliver cyclone, and an SKC DPM cassette from SKC, Inc., Eighty-Four, PA. The SKC DPM cassette contains a single stage impactor and two stacked 37 mm diameter tissue quartz fiber filters. The pumps are operated at 1.7 l/min. At this flow rate, only aerosols with an aerodynamic diameter (D_{50}) smaller than 0.820 μm reached the collection filter (Olson 2001).

The 1.7 l/min sampling flow rate used by this method is inadequate for obtaining DPM samples in cases where the concentration of DPM is low and sampling times are short. Therefore, this method was not used to collect samples during the tests on the filtration systems.

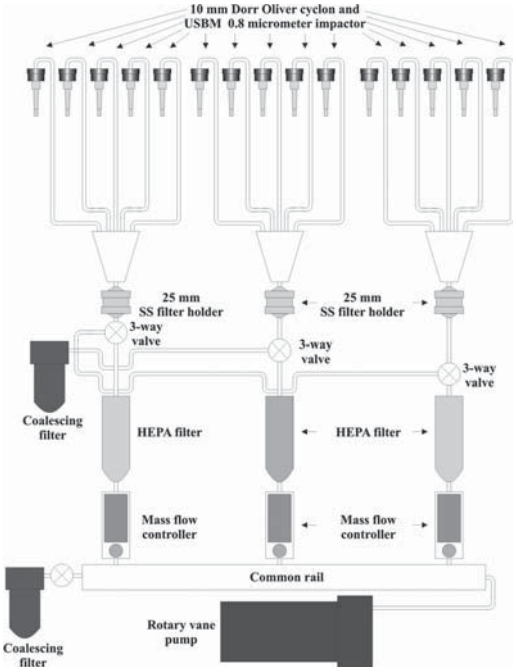

Figure 2. High-volume sampling train.

3.2 *High-volume (HV) method for sampling DPM for carbon analysis*

A HV sampling method was used to collect DPM samples. This high volume sampling train, described in detail elsewhere (Bugarski 2006a), was used to enhance the collection of samples for carbon analysis by increasing the sampling flow rate and decreasing the collection area of the filter. A schematic of the high-volume sampling train is presented in Figure 2. The sampling flow rate was increased by merging flows from five preclassifiers, each consisting of a 10-mm Dorr-Oliver cyclone followed by a U.S. Bureau of Mines (USBM) single stage diesel impactor, into a single stream. A flow rate of approximately 2.0 l/min was maintained through each cyclone and impactor pair. At this sampling flow rate only particles with geometric mean smaller then 0.775 μm were deposited on the filters (Olson 2001).

All five preclassifiers were attached to a symmetrical plenum that distributed a total flow rate of approximately 10.0 l/min uniformly among the five streams. Each of the preclassifier assemblies was connected to the plenum chamber by a 1-m long section

of electrically conductive tubing. The outlet of the plenum was directly connected to a stainless steel 25 mm diameter filter holder containing two stacked 25 mm tissue quartz fiber filters.

The total sampling mass flow rates were maintained using a mass flow controller in the each of the three sampling lines from the 25 mm diameter filter holder. The total volumetric flow rates through each of the sampling streams were measured periodically by inserting a bubble flow meter inline, between filter holders and mass flow controllers. The volumetric flow rates measured during this study were all corrected to ambient conditions. A high volume rotary vane pump was used to draw the sample though the filter.

3.3 *DPM concentration measurements with a Tapered Element Oscillating Microbalance (TEOM) series 1400a ambient particulate monitor*

The TEOM 1400a (Rupprecht & Patashnick Co., Albany, NY) draws air through a filter at a constant flow rate, while continuously measuring the mass accumulating on the filter and calculating near real-time mass concentrations. The sample stream is drawn through this filter from a hollow tapered element that is vibrated at a precisely controlled frequency and connected to the suction side of the sampling system. The vibration frequency of the tapered element decreases as particulate mass collected on the filter increases. By frequently measuring the tapered element frequency, the TEOM calculates the increase in mass of the sample that has accumulated on the filter. The concentration of TPM can be calculated by dividing the accumulated mass by the volume of airflow across the filter during the time period over which the frequency change is measured.

The flow through the instrument is maintained at a constant rate by a mass flow controller. The flow is corrected for temperature and barometric pressure. The internal instrument temperatures are controlled to minimize the effects of ambient temperatures. To prevent condensation and ensure that the sample filter always collects particulates under similar conditions, the TEOM intake is heated to maintain the sampling stream at 50°C.

During this study, the flow rate on the TEOM was set at 1.7 l/min. A cyclone and impactor were used as preclassifiers to the TEOM, allowing only particles with an average aerodynamic diameter (D_{50}) smaller than 0.820 μm to reach the collection filter. The average ambient concentrations of TPM were recorded and saved every 10 seconds. The reported average concentrations for a test were obtained from the difference in filter masses recorded at the same start and stop times used by the particulate samples for carbon analysis.

3.4 *Measurement of size distribution and particle numbers using a scanning mobility particle sizers (SMPS)*

An SMPS was used to periodically measure size distribution and number of particles in the range between 10 and 392 nm. The SMPS consisted of an electrostatic classifier (TSI Inc. Shoreview, MN, Model 3080L) and a Condensation Particle Counter (TSI, Model 3025A).

The flows of monodispersed aerosol were maintained at 0.6 l/min throughout the study. At the established polydispersed aerosol flow rate of 6.0 l/min, the inlet impactor had a cut-off point of 460 nm. The condensation particle counter was operated in high-flow mode to minimize diffusion losses. The samples were collected using 90-second up-scans and 15-second down-scans. The instrument was operated using a dedicated laptop computer and Aerosol Instrument Manager Software from TSI Inc.

The effects of the tested control technologies on size distribution and count concentrations of aerosols in mine air were assessed based on the measurements conducted while the vehicle was performing the portion of the duty cycle at a point nearest to the location of the SMPS.

4 DISCUSSION OF RESULTS

In this section the instrument results from the isolated zone tests will be presented along with a discussion on the applicability of each type of data. The results presented are from tests when the vehicle was outfitted with several diesel particulate filter systems and when the vehicle was fueled with two blends of a water-fuel emulsion.

Figure 3 presents the results from the HV, SSM and TEOM sampling methods observed during the baseline (#1 diesel/muffler) test as well as tests with cold-weather (C-W) and warm-weather (W-W) water-fuel emulsions. As discussed previously, the TEOM results shown here are an average over the sampling period for the HV and SSM methods.

This figure shows that the HV and SSM methods measured similar EC concentrations. The TEOM results show concentrations that are higher then the HV or SSM methods. The additional mass concentrations can be attributed to other DPM compounds such as organic carbon, metals, and sulfates that are not measured by the EC analysis. This additional mass may also contain any particulate, with an aerodynamic diameter smaller than 0. 820 μm, generated during the transfer of ore/waste rock during the test.

Figure 4 presents the results from the HV and TEOM sampling methods observed during the baseline test as well as tests when the vehicle was outfitted with diesel particulate filters.

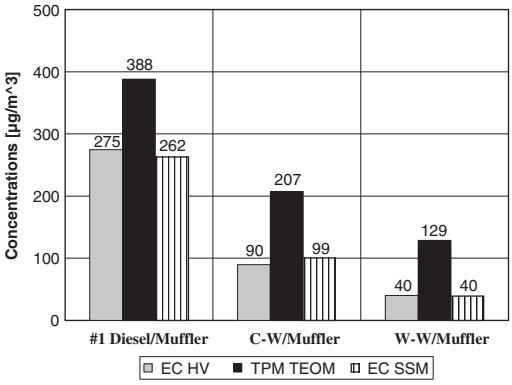

Figure 3. HV, SSM and TEOM results for water-fuel emulsion tests.

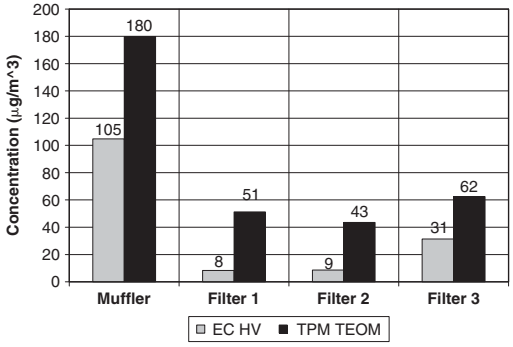

Figure 4. HV and TEOM results for filter tests.

The lack of SSM data on Figure 4 suggests one advantage of the HV method over the SSM. Previous isolated zone tests using vehicles outfitted with diesel particulate filters showed that the SSM was not able to collect enough EC for accurate analysis. However, the increased collection volume of the HV method allowed for successful measurement of these lower EC concentrations. In these tests the TEOM DPM measurements were again higher than the HV EC concentrations. The TEOM was able to effectively measure the DPM concentrations during the filter tests.

Figure 5 presents the semi-continuous (one-minute average) data from the TEOM during the water-fuel emulsion tests. Kelly and Morgan (2002) compared the real-time TEOM measurements with the filter based EPA method and found the ability of the TEOM to measure the transient values of DPM during testing to be a major advantage. Likewise, having a semi-continuous stream of data during these tests is an advantage because this extra data allows for a more thorough inspection of the test data. Evaluation of the semi-continuous data presented in Figure 5 shows the repeatability of the duty cycles during these tests.

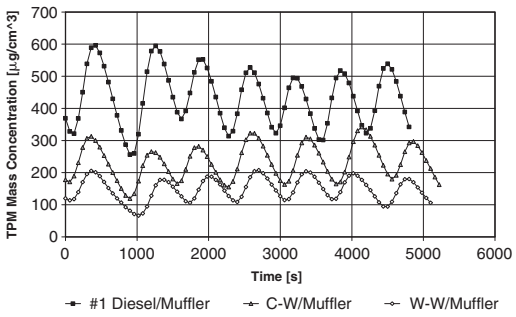

Figure 5. TEOM semi-continuous data during the water-fuel emulsion tests.

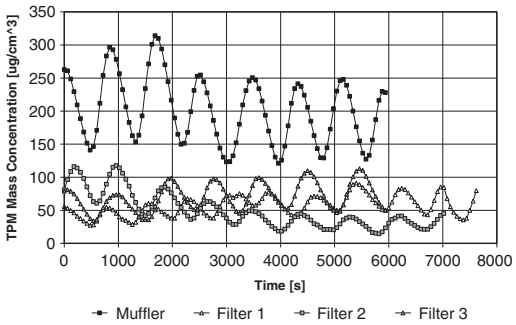

Figure 6. TEOM semi-continuous data during filter tests.

The semi-continuous data also aids in the detection of potential problems during the test. For example if at 3000 seconds the TEOM data showed a major spike or decrease in concentrations, than that is evidence of a potential problem with the test. Data from the HV or SSM methods would not obviously show that a problem occurred.

Figure 6 shows the semi-continuous TEOM data collected during the filter tests. Again this figure shows the repeatability of each duty cycle. This data also shows an interesting aspect of the test using Filter 2. This data shows the DPM concentrations steadily decreasing during the test, indicating that the filter efficiency was improving over the duration of the test. This important piece of information would be impossible to discern using only the HV or SSM results.

The results presented thus far are from mass based measurement methods. However, many researchers have measured DPM using other metrics including particle number concentration or surface area. The advantages and disadvantages of these different metrics for measurement of DPM is currently an area of much research (Kittleson, 2004). One instrument used during the current study to measure particle number concentration was the SMPS.

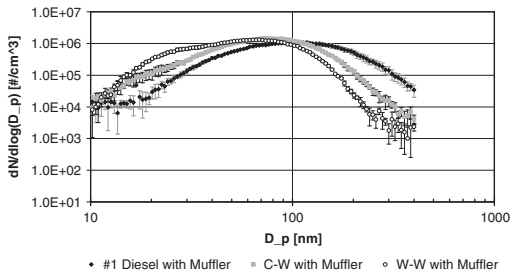

Figure 7. SMPS results from the water-fuel emulsion tests.

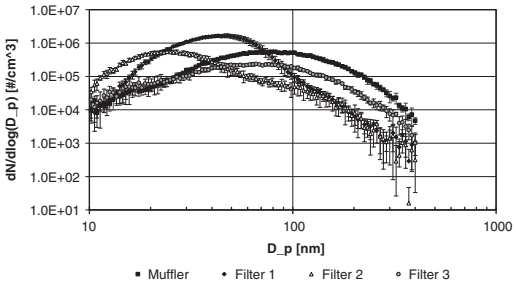

Figure 8. SMPS results from the filter tests.

Table 1. Summary of reviewed measurement methods.

Method (Measurement metric)	Applications	Consideration/ limitation
SSM (Mass concentration)	(1) Personal sampling. (2) Time integrated sampling.	(1) Long sampling time may be required at low DPM concentrations (<80 ug/m^3). (2) Delayed results.
HV (Mass concentration)	(1) Time-limited sampling at low DPM concentrations (< 80 ug/m^3). (2) Time integrated sampling.	(1) Occupational sampling not possible. (2) Delayed results.
TEOM (Mass concentration)	(1) Near real-time sampling. (2) Time integrated sampling.	(1) Occupational sampling not possible.
SMPS (Size distribution and particle number concentration)	(1) Particle size distribution sampling. (2) Real-time sampling.	(1) Occupational sampling not possible. (2) Time integrated sampling not possible.

Figure 7 shows the effects of the two water-fuel emulsions on the aerosol size distributions of the DPM.

The size distributions of the particles observed during the tests with water-fuel emulsions are characterized by lower geometric mean diameter (GMD) and higher peak concentrations than the size distributions observed during the baseline test with #1 diesel. The GMD of the baseline particles was 95 nm, while the GMD for the cold and warm weather water-fuel emulsions were 68 and 55 nm, respectively. The peak particle number concentration for the baseline test with #1 diesel was 1,065,000/cm^3 and was lower than those observed for cold weather (1,449,000/cm^3) and warm weather (1,324,000/cm^3) emulsions. The relative increases in total aerosol number concentrations were (14%) and (16%) for the cold and warm weather water fuel emulsions, respectively.

Figure 8 presents the results of the SMPS data from the filter tests. This data shows that the particle number concentrations were higher for the smallest particles and lower for the larger particles. The size distributions measured during the Filter 1 test were found to be characterized with a bimodal distribution having peak concentrations higher than those observed for the baseline case. The net contribution of the system to the total particle number was also found to be 105% higher than that of the muffler.

The effects of Filter 2 and Filter 3 on size distribution and aerosol concentration were found to be quite different. The size distribution of the particles measured during the test with the Filter 2 was characterized by much lower concentrations in the larger particle size range. On the contrary, the size distributions of the particles during the Filter 3 test had significantly fewer smaller size particles. This is in agreement with the results of the EC, and TEOM measurements, which showed higher EC and TPM reductions for Filter 2 than for Filter 3.

Table 1 presents a summary of the measurement methods presented in this paper and shows their appropriate applications and major considerations and limitations. As can be seen each method discussed has appropriate applications along with certain limitations.

As shown in Figure 3 and Figure 4, the mass measurement results provide evidence that both the water-fuel emulsion and the diesel particulate filters reduced the airborne DPM concentrations. However, the SMPS results tell a slightly different story than that derived from the mass measurements. The SMPS results for both the water-fuel emulsion tests and the filter tests show that while the mass is decreasing the particle number concentration is actually increasing.

Overall, the data in this study emphasize the importance of using instruments that measure different metrics when characterizing DPM and evaluating DPM control technologies. It is important to realize the

necessity of measuring several different metrics to achieve a true understanding of DPM and the effects of DPM control. As shown, control technologies can work very well in controlling one metric but actually increase the concentration of a different metric.

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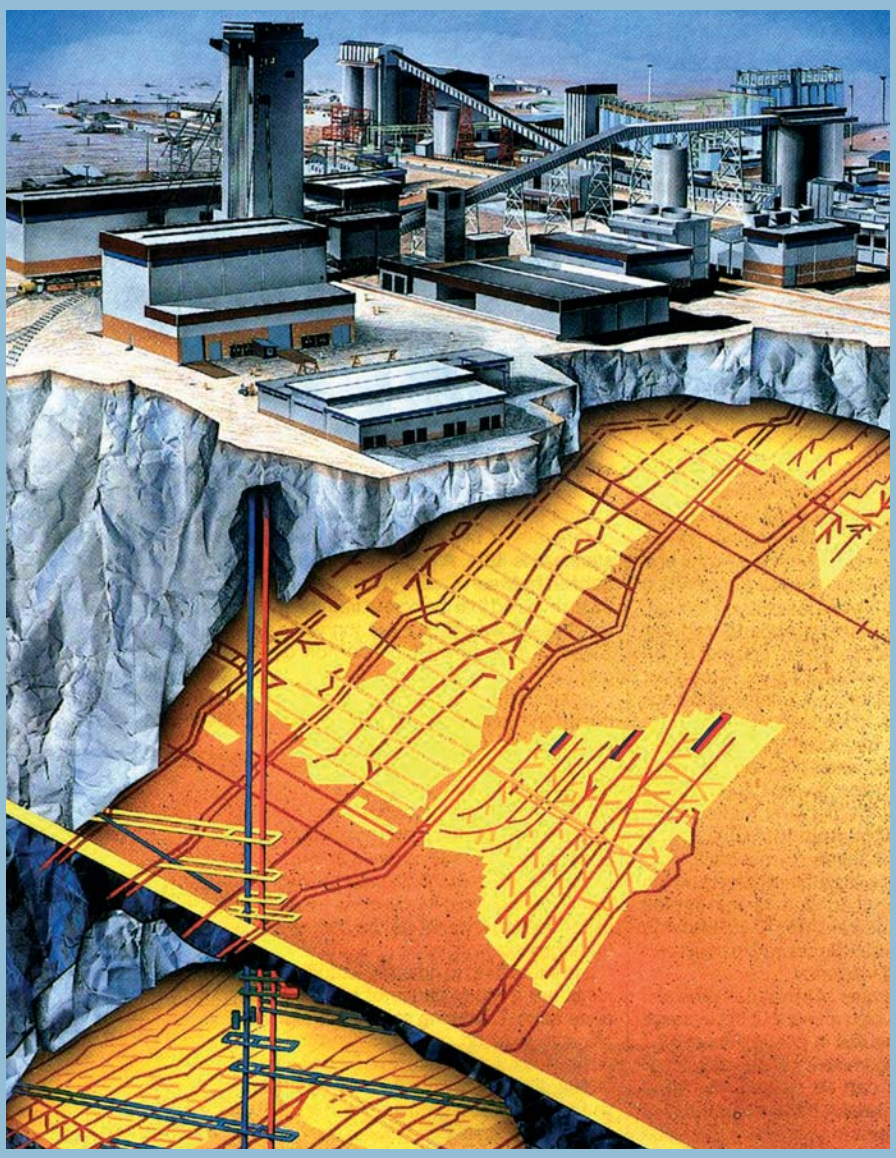

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