The effects of passive diesel particulate filters on diesel particulate matter concentrations in two underground metal/non-metal mines

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ABSTRACT: In 2008, the final rule limiting the personal exposure of underground metal/non-metal miners to diesel particulate matter (DPM) went into effect. In response, metal/non-metal mines are implementing a variety of control technologies to comply with this rule. Two mines have implemented a control strategy where a majority of their larger vehicles, which emit most of the particulate, were retrofitted with passive diesel particulate filters (DPFs). In addition to the DPFs, one mine increased ventilation to dilute the DPM concentrations. A second mine used a combination of DPFs, biodiesel fuel, flow-through particulate filters, ventilation, and enclosed cabs to limit the exposure to DPM to miners. In this study, NIOSH measured the atmospheric concentrations of DPM and gases in these two mines in order to evaluate the effects of the control strategies on the atmospheric DPM concentrations. The results showed that the DPFs substantially reduced the particulate emissions, and in general, the DPM concentrations were below the final limit. However, the DPM concentrations were occasionally over the final limit in areas where vehicles without DPFs were operating and in some areas with lower ventilation rates. These findings indicate that in a few areas of the mine, additional controls such as increased ventilation may be needed to reduce the DPM concentrations below the final limit. NIOSH was also interested in the atmospheric nitrogen dioxide (NO_2) concentrations in these mines, since some passive DPFs can increase NO_2 concentrations. The measured NO_2 concentrations did not exceed 5 part per million (ppm) (ACGIH STEL) at these mines.

1 Introduction

Diesel particulate matter (DPM) is believed to be a possible carcinogen (IARC, 1989; NIOSH, 1988; US EPA 2002). Further, diesel exhaust has been linked to health effects such as eye and nose irritation, headaches, nausea, and asthma (Kahn *et al*., 1988; Rundell *et al*., 1996; Wade & Newman 1993). Because underground miners may be exposed to some of the highest levels of diesel exhaust in the United States, the Mine Safety and Health Administration (MSHA) has promulgated rules to limit the exposure of miners to DPM (MSHA, 2001; 2006). In an effort to decrease DPM concentrations and comply with this rule, mines are implementing a variety of control technologies. One form of control technology being used is the diesel particulate filter (DPF).

DPFs employed on the equipment in underground metal/non-metal mines are usually a ceramic or silicon carbide wall-flow monolith type. The particulate in the tailpipe is collected and builds up onto the filter. At some point, if the filter is not replaced or the particulate is not removed, the build-up of the particulate will cause high back pressure on and possible damage to the engine.

The particulate can be removed from the filter by regenerating the filter, which entails oxidization of the particulate to form CO and CO_2. Filters must reach a temperature above 500°C to regenerate. In order to decrease the temperature needed for regeneration, filters are sometimes coated with a catalyst such as platinum to enhance oxidation, or a catalyst is placed in the fuel system (fuel-borne catalyst) and onto the filter along with the particulate. These catalyzed filters can regenerate at temperatures ranging between 250 and 300°C.

There are two types of regeneration schemes - termed active and passive - commonly used to regenerate DPFs for underground mining equipment. The active filter relies upon an outside source to produce the heat to regenerate the filter. This can entail taking the loaded filter out of the vehicle to be regenerated or taking the vehicle out of production and regenerating the filter while it is still on the vehicle. The passive filter is usually catalyzed and regenerates while the vehicle is operating, using the heat from the engine exhaust to regenerate the filter. Thus, the passive filter offers the advantage of the vehicle not being taken out of service and the filter not needing to be replaced. However, passive filters cannot be used on all pieces of equipment, since not all vehicles are able to produce exhaust temperatures high enough for self regeneration. Some catalyzed passive filters can also cause an increase in NO_2 emissions, which could result in a health hazard.

Ceramic filters have proven to be effective on some underground mining equipment, with reductions of over 75% in total DPM and over 90% in elemental carbon (Bugarski *et al*,. 2005, 2006; MSHA, 2005; Roegner *et al*., 2002). In addition, on a loader under actual mining conditions, the use of a passive DPFs resulted in self regeneration using the exhaust temperatures of the vehicle and no significant NO_2 concentration increase (Noll & Patts, 2009).

Due to the high reductions reported and the field successes of passive DPFs, two mines have implemented a DPM control strategy involving passive DPFs. One mine (Mine A) installed passive DPFs on the mine's larger vehicles that have exhaust temperatures high enough to allow regeneration. In order to further dilute the DPM, the ventilation in the mine was also increased and redirected. Another mine (Mine B) also installed passive DPFs on most of their larger vehicles. Instead of DPFs, some of the smaller vehicles were retrofitted with flow through filters (FTF) because particles do not build up on FTFs. FTFs are specialized diesel oxidation catalyst (DOC) filters that utilize substrates with some capacity to capture particulates. Even when FTFs are saturated with particulate and regeneration does not occur, particulates do not build up and are still able to flow through. When FTFs were used, previous studies have reported a DPM reduction efficiency ranging from 30 to over 50% efficiency (ARB 2008, Okawara *et al*., 2005, Choi et al. 2007). Mine B also used a biodiesel blend (70% biodiesel/30% ultra low sulphur diesel) to further lower emissions since biodiesel has been shown in previous studies to reduce DPM emissions (Bugarski *et al*., 2006). The two goals of this study were to: (1) evaluate the control strategies being used in these two mines; and (2) assess how effectively the passive DPFs were functioning. To meet these goals, the concentrations of DPM in the mines were measured, information was gathered on any back pressure problems when using the DPFs, and ambient NO_2 concentrations were measured.

2 Methods

2.1 Sampling baskets

To collect diesel particulate matter at various locations in Mines A and B, several different types of samplers were employed and placed into a basket as seen in Figure 1. At least two SKC DPM cassettes attached to MSA Elf sampling pumps (flow rate of 1.7 lpm) were used to collect particulate samples to be analyzed for elemental and total carbon. This type of measurement was taken because it is used by the Mine Safety and Health Administration (MSHA) for DPM compliance sampling (MSHA 2005). The SKC DPM cassette is a size-selective device (impactor) which collects particles less than 0.8 µm in diameter. This sampling technique is effective at segregating the diesel particles from the larger airborne material such as dust, since the size of DPM aerosol is usually less than 0.8 µm, while dust particles in mines are usually larger than 0.8 µm (Noll *et al.*, 2006). A quartz filter inside the cassette was used to collect particulate, and the cassette was later analyzed for elemental carbon (EC) and total carbon (TC) using the NIOSH method 5040 at the NIOSH laboratory in Pittsburgh.

EC and TC are used as surrogates for DPM because direct measurement of DPM lacks the required sensitivity and can be prone to interferences (Noll *et al.*, 2006). Because TC accounts for over 80% of DPM and can be measured accurately (Pierson & Brachaczek, 1983: Noll *et al.*, 2006, 2007), MSHA uses a TC value (160 µg/m^3) for the final permissible exposure limit (PEL). TC, however, is prone to interferences from cigarette smoke and oil mist. Therefore, because EC is specific to DPM and correlates well to TC, a compliance sample is determined using both the TC and EC results (MSHA, 2005, Noll *et al.*, 2007). First, the TC value from a personal sample is determined. If this value is above the final limit, then in order to discount the influence of any interferences, an adjusted TC value is calculated by multiplying the EC value of the personal sample by a conversion factor. This conversion factor or TC/EC ratio is determined from TC and EC analysis of samples collected downstream of the miner in an area assessed to be clear of significant interferences, yet representative of the air the miner is breathing. Both the analyzed TC value from the personal sample and the calculated TC value from the TC/EC ratio must be above the final limit for the sample to be out of compliance.

For the sampling at Mines A and B, a Vaisala GM70 was used to measure CO_2 concentrations every minute. An ICx, or NIOSH prototype, DPM monitor was used to assess the concentration of EC in mine air on a continuous basis (Noll *et al.*, 2007; Janisko & Noll 2008). The performance of the ICx has been shown to correlate well with results from SKC DPM cassettes analyzed for EC using the NIOSH 5040 method (Noll *et al.*, 2007; Janisko & Noll, 2008). ITX multi-gas instruments were used to measure NO_2 concentrations.

Figure 1 A sampling basket hanging along the rib.

2.2 NIOSH method 5040

After samples were collected onto the quartz filters, they were analyzed for elemental and total carbon using NIOSH Method 5040 (Birch, 2004) at NIOSH in Pittsburgh using the Sunset Laboratory carbon analyzer This analytical method analyzes for organic carbon (OC) and EC collected on the filter in two different stages. In the first stage, the OC is evolved in a pure helium (He) atmosphere by ramping the instrument's oven temperature through four progressively higher programmed temperature steps, with the last step being at about 870°C. The EC on the filter does not evolve in this atmosphere because there is no oxygen (O_2) available with which it can react. The evolved OC is oxidized to carbon dioxide (CO_2), reduced to methane (CH_4), and finally measured using a flame ionization detector (FID). In the second stage, the EC is measured, by reducing the oven temperature to about 600°C and then again raising the temperature to about 900°C in a He/O_2 atmosphere (O_2 is now present to react with the EC to form CO_2), the EC evolves to CO_2. The EC is then measured in the same way as the OC with an FID. OC and EC are then summed to obtain TC. The NIOSH Method 5040 also optically corrects for pyrolysis (charring) of OC.

NIOSH 5040 has been shown to meet the NIOSH accuracy criteria and has yielded good results for inter-laboratory testing (Birch, 2004).

2.3 Sampling at Mine A

For three days in a row, sampling baskets (see Section 2.1) were used to collect DPM in different areas of the mine. On Day 1, a basket was placed on a loader (Loader 1) equipped with an Engelhard passive ceramic DPF and operated in a face area. Three baskets were hung along the rib in different areas as shown in Figure 1. Two baskets with SKC DPM cassettes solely for DPM sampling and subsequent EC and OC analysis were set up in two exhaust air courses. On this day, all of the larger vehicles were equipped with DPFs.

On Day 2, baskets were not placed on any vehicles, but one basket was hung at the face area. Three baskets were placed in the same locations as on day one. Two baskets for NIOSH 5040 samples only were placed in the same exhaust air courses as on day one.

On Day 3, one basket was placed on a loader (Loader 2) equipped with an Englehard passive ceramic DPF. The loader operated at a face. Another basket was attached to a backfill jammer that had no control technology; the jammer worked at a different section than Loader 2. Two baskets were placed in two different areas of the mines. Two baskets solely for NIOSH 5040 samples were again placed in the exhaust air courses.

The samples were collected for about 6 hours each day. Most of the larger vehicles in this mine had Englehard or DCL ceramic passive DPFs. A vane anemometer was attached to an extendable rod and was used to collect air velocity readings for one minute in the sample areas, and entry cross-sectional measurements were recorded.

2.4 Sampling at Mine B

For three days in a row, sampling baskets (see Section 2.1) were used to collect DPM samples in different areas of the mine. Table 1 lists the locations of the baskets for each day and notes the sampling times.

Relevant observations made during sampling were the following: Mucker 1 was not operating for the entire shift. Drilling was also occurring near Mucker 1 and oil mist could have affected some of the TC measurements. The basket on Mucker 4 was first attached to Mucker 3 with a DOC, but this mucker was not being used. Therefore, at 9:30 a.m., the basket was transferred to Mucker 4. The real time data (EC and CO_2) did not record for Truck 3 due to instrument errors.

Table 1 Location of Sampling Baskets for Mine B

Day	Location	Sampling Time
1	on truck 1 with a DCL Mine-X BM ceramic passive DPF used for hauling ore from the face to the crusher	4-5 hours
2	on mucker 1 with diesel oxidation catalyst (DOC) used for cleaning up face area	over 6 hours
2	on mucker 2 with NETT ceramic passive DPF used at a face area	over 6 hours
2	on truck 2 with NETT ceramic passive DPF	over 6 hours
2	exhaust	over 6 hours
3	on mucker 4 with Englehard ceramice passive DPF used at face	over 6 hours
3	on truck 3 with NETT ceramic passive DPF	over 6 hours
3	on mucker 5 with Mann Hummel sintered metal passive DPF used at face	over 6 hours
3	exhaust	over 6 hours

Ventilation measurements were taken at the faces and different areas of the mine using the same procedure as for Mine A.

2.5 Dynamic Blank Correction

Quartz filters have been found to absorb vapour phase OC, which is not traditionally recognized as part of DPM or other types of particulate carbon, and thereby, this absorption will contribute a positive bias in DPM TC results (Noll & Birch 2008). To correct for this bias, a second filter was placed behind the sample filter, resulting in two filters positioned in tandem (Noll & Birch, 2008). In theory, only the sample filter collects particulate OC, but both filters absorb about the same amount of vapor phase OC. Results from the second filter were therefore subtracted from the sample filter OC values to correct for the absorbed vapour phase OC.

2.6 Normalizing Data with CO_2 Concentration

The EC results obtained during this study were divided by the CO_2 concentrations (background CO_2 was subtracted out) to determine the EC to fuel burned ratio. Fuel consumption is directly proportional to CO_2 mass emissions (Bugarski *et al*., 2005, 2006; Schnakenberg *et al*., 1986;, Johnson & Carlson., 1986). Therefore, the EC to fuel burned ratio can then be determined by dividing the EC by CO_2 concentrations.

The EC values can be affected not only by the DPFs but also by load on engine, ventilation, vehicle time of operation, and daily haulage. To determine how the usage of DPFs alone affect the EC values, previous studies have used CO_2 concentrations (fuel usage) to normalize the EC value when comparing a vehicle equipped with and without a DPF under similar engine load conditions. CO_2

concentration is not significantly affected by the usage of a DPF but can be used to correct for changes in ventilation, time of vehicle operation, and daily haulage quantities. (Bugarski *et al.*, 2006). Table 2 shows typical EC/CO$_2$ ratios measured for mining vehicles operated in an isolated zone study, where the only source of EC was from the vehicle being tested (Bugarski *et al.*, 2006). Unlike in the isolated zone study, the EC/CO$_2$ ratios from Mines A and B may be influenced by vehicles operating upstream. However, the exhaust from those vehicles working in the same area should produce the largest contribution to the ratio. Therefore, if DPFs reduce the DPM as reported in other studies (by over 75%), the EC/CO$_2$ ratios should be expected to be significantly less in areas where vehicles employ DPFs compared to areas where vehicles use no control technology.

Table 2 EC/CO$_2$ Ratios from a 2003 Isolated Zone Study

	baseline	**with DPF**
Vehicle	**EC/CO$_2$**	**EC/CO$_2$**
Haul Truck 128	0.49	0.02
Haul Truck 133	0.84	0.01
mucker 942	0.43	0.06
mucker 506	0.55	
mucker 526	0.42	

Table 3 EC/CO$_2$ Ratios for Samples Taken on Vehicles

Mine	Vehicle	EC/CO$_2$
A	Backfill Jammer without DPF	0.42
A	Loader 1 with DPF	0.04
A	Loader 2 with DPF	0.05
B	Mucker 1 with DOC	0.81
B	Truck 1 with passive DPF	0.05
B	Truck 2 with passive DPF	0.05
B	Mucker 2 with passive DPF	0.12
B	Mucker 4 with passive DPF	0.19
B	Mucker 5 with sintered metal DPF	0.16

Note: See Methods section for detail description of control technology used on each vehicle in Table 3.

3 Results and Discussion

3.1 Effects of DPFs on DPM

As seen in Table 3, the EC/CO$_2$ ratios for vehicles with no DPFs in mines A and B were 0.42 and 0.84. These ratios are similar to the ones reported by Bugarksi *et al.* (2006) for mining vehicles (see Table 2: 0.42-0.84). The ratios determined on vehicles with DPFs were significantly lower (0.01-0.19) than the ratios reported for similar types of vehicles without DPFs performing similar tasks in both the isolated zone and this field study. These ratios imply that the DPFs resulted in a significant decrease in DPM emissions.

The ratios from vehicles with DPFs in Mine A and the trucks in Mine B were similar to the ratios observed for vehicles with DPFs in the isolated zone study. However, in Mine B, some of the EC/CO$_2$ ratios from vehicles with DPFs were higher than those in the isolated zone. This could be due to the effects of vehicles with no emission controls, vehicles with FTFs, less efficient DPFs, or DPFs with slight leaks.

3.2 DPM Concentrations in the mines

In this study, the concentrations of DPM were measured at many locations in the mine to determine the overall effects of the control strategies employed. Tables 4 and 5 show the concentrations of TC and EC from Mines A and B. The TC$_{adj}$ was calculated by a procedure similar to MSHA compliance sampling (MSHA, 2005). However, these concentrations do not necessarily represent miner exposure levels, since the time that miners were working in these areas is unknown and because enclosed cabs were used in some cases.

As seen in Table 4, for most areas in Mine A, the concentration of DPM was below the final PEL (160 µg/m^3 TC). However, sometimes this was not the case. The average concentration for the shift was above the final limit when vehicles without DPFs were operated (Table 4: area (on Jammer)). The average concentrations of samples on Loaders 1 and 2 were also slightly above the final limit, even though both vehicles were equipped with DPFs. These areas where Loader 1 and 2 were working had the lowest measured ventilation rates.

Table 4 EC and TC Concentrations from Areas in Mine A

Area	EC (µg/m^3)	TC (µg/m^3)	TC adj (µg/m^3)	Ventil-ation (cfm)
Area (on jammer)	447.50	515.23	671.26	25,358
Face (on loader 1)	125.22	208.44	187.82	16,696
Face (on loader 2)	126.92	181.90	190.37	23,513
Face (area)	75.45	118.85	113.17	16,696
Cross-section	80.98	117.76	121.47	162,000
Cross-section	63.97	69.94	95.96	162,000
Cross-section	31.37	44.27	47.05	102,000
Cross-section	26.58	43.76	39.87	102,000
Cross-section	51.99	66.71	77.99	102,000
Cross-section	60.32	86.93	90.47	102,000
Cross-section	50.85	65.79	76.28	102,000
Cross-section	72.10	90.60	108.15	102,000
Exhaust Air Course	78.00	115.48	117.00	244,198
Exhaust Air Course	64.98	101.11	97.48	244,198
Exhaust Air Course	100.31	122.67	150.46	244,198
Exhaust Air Course	57.48	84.31	86.23	27,295
Exhaust Air Course	36.09	52.24	54.14	27,295
Exhaust Air Course	85.08	118.69	127.62	27,295

TC adj = EC x 1.5: 1.5 being the highest TC/EC ratio from the exhaust samples

In general, the DPM control strategy used in Mine A resulted in concentrations below or close to the final PEL. However, higher DPM concentrations were observed in areas where vehicles without DPFs were operating and in areas with lower ventilation. Therefore, in some areas, additional strategies such as DPFs on other vehicles, increased ventilation, use of a biodiesel blend, administrative controls, or enclosed cabs should be employed to further reduce the DPM concentrations.

Table 5 EC and TC Concentrations from Areas in Mine B

Area	EC (µg/m³)	TC (µg/m³)	TC adj	Ventilation
Face (mucker 1)	99.50	204.06	149.25	5000
Face (mucker 2)	81.40	111.37	122.10	9000
Face (mucker 4)	116.30	147.87	174.45	78000
Face (mucker 5)	113.70	143.92	170.55	172000
Areas (on truck 1)	26.19	53.63	39.29	
Areas (on truck 2)	45.44	79.03	68.16	
Areas (on truck 3)	152.33	192.93	228.49	
Exhaust Air Course	136.66	209.47	204.98	39000
Exhaust Air Course	129.28	159.87	193.92	172000

TC adj = EC x 1.5 : 1.5 is the highest TC/EC ratio from exhaust samples

As seen in Table 5, just as in Mine A, the DPM concentrations in most areas in Mine B were below the final limit. However, some areas had average DPM concentrations about 25% higher than the PEL. Mucker 1 was not equipped with a DPF, but the average concentration of samples on Mucker 1 was not above the final PEL. This was probably due to Mucker 1 only operating for a limited time. Mucker 1 showed one of the highest EC to fuel burned ratios for the mining vehicles (see Table 3), and during operation its concentration of DPM was about 150 µg/m^3 EC (225 µg/m^3 TC$_{adj}$) (see Figure 2).

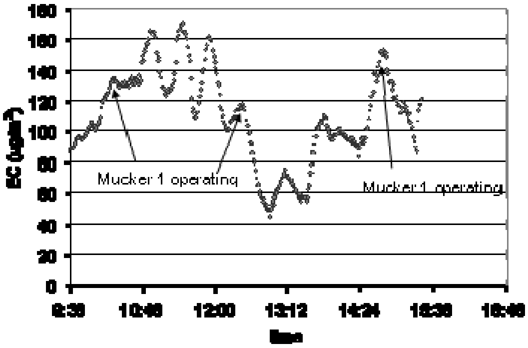

Figure 2 Real-time EC Concentrations for Mucker 1 in Mine B

Concentrations above the final limit can be the result of the influence of vehicles without DPFs and lower ventilation rates. In order to lower the concentration of DPM in the areas that fell above the final limit, Mine B could retrofit DPFs on some of the mine's other vehicles, increase ventilation in certain areas, or implement administrative controls.

3.3 Regeneration

Discussions with personnel from Mines A & B revealed that the vehicles equipped with passive DPFs seem to regenerate well. The use of DPFs did not result in backpressure problems and the equipment did not have much down time due to filter problems.

3.4 Nitrogen Dioxide Concentrations

A concern when using passive DPFs is that some can increase nitrogen dioxide (NO_2) emissions, resulting in higher ambient concentrations (Bugarski *et al.*, 2006). As seen in Figures 3 and 4, the NO_2 concentrations did not exceed 5 ppm (ACGIH STEL) with the ventilation used in these mines. In fact, for most areas in the mines, the NO_2 concentration did not exceed 3 ppm (ACGIH TLV TWA). In one area (on Loader 1) that was the least ventilated in Mine A, the NO_2 concentration did exceed 3 ppm at times, but the time weighted average was below 3 ppm.

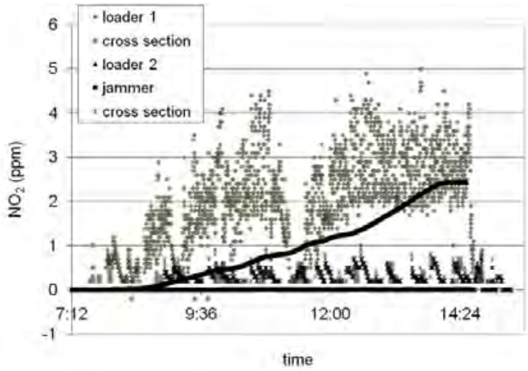

Figure 3 Nitrogen Dioxide (NO_2) Concentrations measured in Mine A.

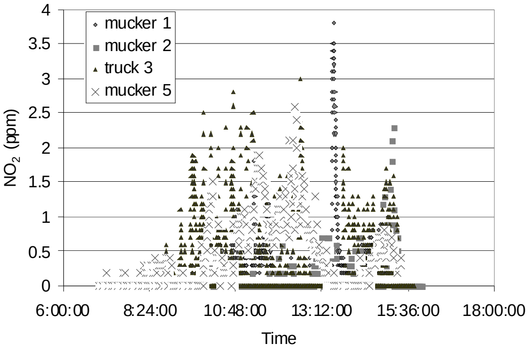

Figure 4 NO_2 Concentrations measured in Mine B.

4 Conclusion

The two mines studied have successfully implemented DPM control strategies and are continuing to investigate ways to lower DPM concentrations for their miners. The control strategies employed resulted in concentrations below MSHA's final limit in most cases. However, the concentrations were slightly above the limit in some areas operating vehicles with DPFs where the ventilation was relatively low. The concentration of DPM was also higher than 160 µg/m^3 TC when some vehicles without DPFs were operating for an extended time.

The DPFs on the vehicles seemed to be effective in that they reduced DPM significantly, seemed to be regenerating and not causing back pressure problems, and the ambient NO_2 concentrations measured were below the ACGIH STEL (5 ppm). Ventilation as part of their control strategy was necessary for these mines, for the data suggested that the DPFs alone would not lower concentrations below the final limit. Ventilation also gives the advantage of diluting other contaminants like NO_2.

Additional controls may be needed to lower concentrations in some areas of the studied mines. Such controls could include the use of DPFs on more equipment; increased or redirected ventilation; administrative controls, such as limiting the number of vehicles in an area; and the use of enclosed cabs.

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