

Effects of a diesel particulate filter regeneration process on aerosols in an underground mine

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Abstract This study was conducted to evaluate the effects of a diesel particulate filter (DPF) regeneration process on the concentrations and size distributions of aerosols in an underground mine. Two active regeneration strategies were examined for an electrically regenerated sintered metal fiber filtration system, and the effects were compared with those observed for a muffler and the same system operated in a passive configuration. The effects were assessed for three steady-state engine operating conditions. The number and mass concentrations and size distributions of aerosols in mine air were found to be strongly affected by the exhaust configuration, engine operating conditions and the regeneration process. When the system was operated in active configurations, the concentrations exhibited a transient and cyclic nature. At light load conditions, the distributions of aerosols in mine air were dominated by accumulation mode aerosols for all exhaust configurations and regeneration strategies. High concentrations of nucleation aerosols were observed when the DPF system was used and the engine was operated at high load conditions. A positive correlation between accumulation of particulate matter in the filter and the efficiency of the filter in removing accumulation mode aerosols was observed for all conditions. In the case of high engine load, reductions in accumulation mode aerosol concentrations were linked to a substantial increase in number concentrations of nucleation mode aerosol. Overall, the filtration system was found to be very effective in reducing total aerosol mass and elemental carbon concentrations for all engine operating conditions. However, the system was substantially more effective in passive than in active regeneration configurations.

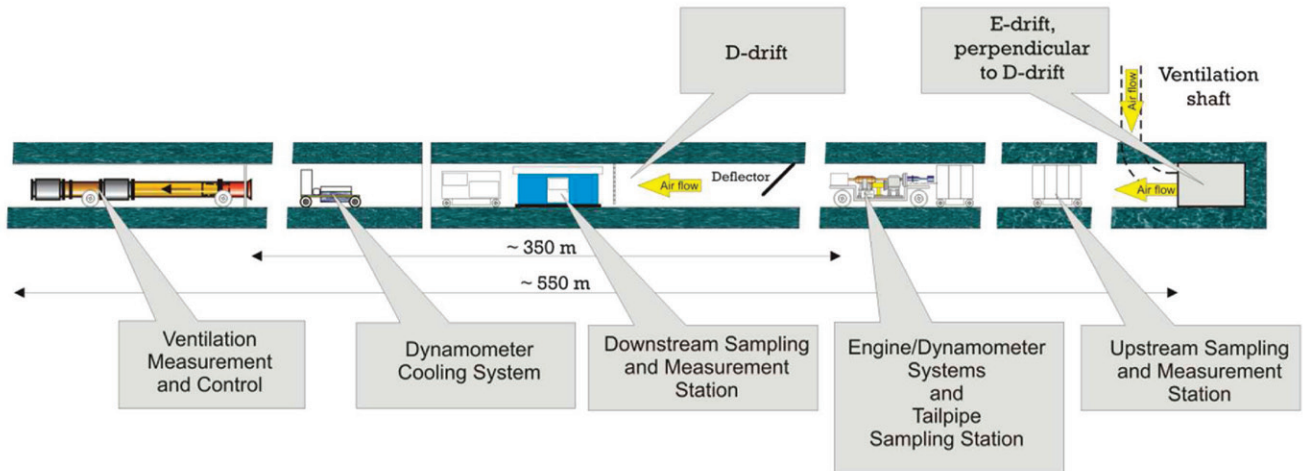
Introduction

The curtailment of diesel particulate matter (DPM) and toxic gaseous emissions using various exhaust after-

treatment technologies is considered to be an important component of an integrated strategy implemented by the underground mining industry to meet Mine Safety and Health Administration (MSHA) regulations limiting exposure of underground coal (66 *Fed. Reg.* 27864, 2001) and metal and non-metal (71 *Fed. Reg.* 28924, 2006) miners to DPM. These technology-forcing regulations promoted the implementation of diesel particulate filter (DPF) systems in underground mines. DPF systems with wall-flow monolith and sintered metal elements are recognized to be effective in trapping DPM (Mayer et al., 2000; Vaaraslahti et al., 2004; Kitelson et al., 2006) and could be used for reducing exposure of underground miners to DPM (Bugarski et al., 2006a; Bugarski et al., 2006b; Bugarski et al.,

2009). A rugged environment, a wide variety of specialized heavy- and light-duty applications, confined space with limited ventilation and NO₂-specific occupational exposure limits are some of the underground mining-specific technical challenges that need to be addressed prior to wide implementation of DPF systems in underground mines.

A DPF element requires periodic removal of the collected DPM (regeneration) to prevent excessive engine backpressure buildup. Active DPF systems, similar to the one evaluated in this study, that are regenerated using electrical energy available on board the vehicle are a potential solution for a number of underground mining applications where equipment has been operated over medium-duty and light-duty cycles and exhaust gas tempera-

Figure 1**NIOSH Diesel Laboratory in the D-drift of Lake Lynn Experimental Mine.**

tures are often below those needed for passive catalytic regeneration. These systems are also perceived as an alternative to the DPF systems with filter, prefilter and diesel oxidation catalyst elements wash-coated with platinum-based catalyst formulations, which are found to promote NO to NO₂ conversion (Mayer et al., 2003) and have the potential for an undesirable increase in NO₂ concentrations in an underground mining environment (Bugarski et al., 2006a; Bugarski et al., 2006b).

The diesel particulates are, in general, distributed in accumulation and nucleation modes (Kittelson, 1998). The particle mass is controlled by accumulation mode agglomerates. In the presence of a pronounced nucleation mode, particle total number count is dominated by these particles. The solid core of accumulation mode particles is primarily made of elemental carbon, while semivolatile fractions are primarily made of organic carbon. Nucleation mode particles primarily consist of liquid particles (Vaaraslahti et al., 2004) that can be evaporated considerably between 150° and 230° C (Biswas et al., 2008) and might have a nonvolatile core with volatile species condensed on it (Rönkö et al., 2007). The nucleation mode particles downstream of catalyzed DPFs were found to consist mainly of sulfates (Kittelson et al., 2006; Vaaraslahti et al., 2004; Grose et al., 2006). Without a DPF, the formation of the nucleation mode was observed only at low engine loads, and those particles were found to be made primarily of hydrocarbon compounds (Vaaraslahti et al., 2004).

Due to the very short duration of the regeneration process for a continuously regenerated DPF, the increases in emissions of regulated and nonregulated pollutants during that process are typically considered negligible compared to those produced during normal operating conditions. The DPF regeneration process was found to increase hydrocarbon, CO and particulate mass emissions (Bikas and Zervas, 2007). Information on the effects of electrical DPF regeneration on emissions is not readily available in the literature.

The objective of this study was to evaluate the effects of an electrically regenerated sintered metal fiber DPF system on the concentration, size distribution and carbon composition of nano and ultrafine aerosols in mine air downwind of the exhaust discharge. Two active regeneration strategies were examined for an electrically regenerated sintered metal fiber filtration system, and the effects were compared with

those observed for a muffler and the same system operated in passive configuration.

Experimental methodology

The DPF system with sintered metal fiber filtration elements (Model RH305-M) was supplied by Rypos Inc., Holliston, MA. This type of DPF is certified by the California Air Resources Board as a Level 3 Plus device for stationary emergency standby generator and pump applications and verified by MSHA (MSHA, 2009). The evaluated system had three stacks of active sintered metal fiber filter elements. Two of those stacks were equipped for active (electrical current) regeneration (RA). The third stack was not equipped with active components. Two solenoid actuated valves were used to control exhaust flow through the system. A diesel oxidation catalyst (DOC) with proprietary formulation was installed at the outlet of the DPF system. The system was originally designed to be operated on 12 VDC power vehicle's system. In this study, the system was powered via a transformer from 220 VAC grid power. When power was not supplied to the system, both solenoids remained open and the system was operated in passive regeneration (RP) configuration.

The system was evaluated in the RP configuration and in two RA configurations. For the first active configuration (RA1), the system was programmed to initiate two-minute regeneration in regular 14-minute time intervals. In the case of the second active configuration (RA2), the DPF system was programmed to initiate five-minute regeneration every time engine backpressure reached approximately 7.5 kPa (30 in. H₂O). Prior to the start of the first evaluation run, the DPF system was conditioned in RA1 mode with the engine operating at intermediate speed and full load for approximately 30 hours. A baseline was established for each operating condition using a generic muffler installed in place of the DPF system. Those tests were noted as being conducted in the muffler configuration, as compared to the DPF configurations.

Because of the sensitivity of diesel aerosols to sampling and dilution conditions (Khalek et al., 2000), the measurements were performed directly in a simulated occupational setting using the National Institute for Occupational Safety and Health (NIOSH) Diesel Laboratory (Bugarski et al., 2009). This laboratory has been developed in the D-drift of

Table 1**Engine operating conditions.**

Mode	Engine speed rpm	Torque Nm	Power kW
M1	2,950	55.6	17.2
M2	2,950	111.2	34.4
M3	2,100	69.1	15.2

the NIOSH Lake Lynn Experimental Mine (LLEM) and is designed to allow evaluation of control technologies in an underground environment. The major components of the laboratory (Fig. 1) are an engine/dynamometer system, three sampling and measurement stations, and a ventilation measurement and control system.

A mechanically controlled, naturally aspirated, directly injected Isuzu C240 diesel engine was coupled to the water-cooled eddy current dynamometer. The engine was operated over three steady-state conditions (Table 1). Conditions M1 and M3 are representative of light loads, where exhaust temperatures are relatively low, and condition M2 is representative of high load conditions, where exhaust temperatures are relatively high.

The average exhaust temperatures at the inlet to the DPF system for M1, M2 and M3 were found to be 303°, 521° and 248° C, respectively.

The engine was fueled with ultra low sulfur diesel (ULSD) with 10 ppmS by mass, supplied by Guttman Oil (Belle Vernon, PA).

Fresh, unconditioned air was supplied to the LLEM via a ventilation shaft located in the E-drift (Fig. 1). An auxiliary fan and a subsonic Venturi meter were used to maintain and measure a constant flow of fresh air through the drift throughout the tests. The measurements showed an average volumetric flow rate of 5.76 ± 0.05 m³/s. The very low test-to-test variability in flow rate eliminated the need for normalization of the data with respect to ventilation rate. The average exhaust dilution ratios for M1, M2 and M3 engine operating modes were calculated to be 133, 140 and 186, respectively. The average ambient temperatures upstream of the engine were between 13.8° and 20.0° C. The corresponding average ambient temperatures at downstream measurement station ranged between 14.6° and 22.6° C.

Measurements

The net effects of the DPF regeneration process on characteristics of aerosols in mine air were determined by comparing the results of aerosol size distribution and concentration measurements performed at the downstream and upstream ambient monitoring stations. The upstream ambient monitoring station was located approximately 60 m upwind of the engine and dynamometer system, and the downstream station was located about 60 m downwind of the same system. For each combination of the aftertreatment configuration and engine operating conditions, the data and samples were collected over a single three-to-eight-hour long test. The initial hour of each test was dedicated to achieving thermodynamic and concentration system equilibrium. The measurements were initiated at the beginning of the second hour.

The aerosol number concentrations, size distributions and mass concentrations were measured at a single point at each of the measurement stations. The width and height of the D-drift are 6 m and 1.9 m, respectively. The measurement points were located in the middle of the drift opening and about 1.5 m off the floor. A scanning mobility particle sizer (SMPS) (Wang and Flagan, 1990) Model 3936 from TSI (St. Paul, MN) was used to measure size distribution and number concentrations of aerosols at the upstream station. A fast mobility particle sizer (FMPS) (Johnson et al., 2004) Model 3090 from TSI (St. Paul, MN) was used at the downstream station to measure size distribution and number concentrations of aerosols. The SMPS and the FMPS were used to measure aerosols with electrical mobility diameters ranging from 10-400 nm and 5.6-560 nm, respectively. The full scan time was 120 s for the SMPS and 1 s for the FMPS. The higher time resolution of the FMPS allowed for better temporal tracking of transient processes occurring during DPF regeneration and transit of the aerosol to the downstream station. Tapered element oscillating microbalance (TEOM) Series 1400a ambient particulate monitors from Thermo Scientific (Franklin, MA) were used at both the downstream station and the upstream station, to measure total particulate matter mass concentrations. A 10-mm Dorr-Oliver cyclone followed by a DPM cassette (SKC, Eighty Four, PA) with its collection filter removed were used to preclassify aerosols entering the TEOM, allowing only particles with an average aerodynamic diameter ($_{50}d_{ae}$) smaller than 0.82 μ m to reach the TEOM.

For the tests with the muffler and the DPF system in RP (only M1-M3 conditions) and RA2 configurations, three DPM filter samples for carbon analysis were collected at the downstream station. Two DPM filter samples were concurrently collected at the upstream stations to establish background carbon concentrations. The samples were analyzed for elemental carbon (EC) content using the NIOSH Analytical Method 5040 (NIOSH, 1999).

Results and discussion

Background number and mass concentrations. In an effort to preserve authentic underground mine environment conditions, air from the mine ventilation system was not conditioned and filtered. Therefore, it was necessary to continuously monitor background aerosol concentrations. The SMPS was used to measure the number concentration and size distribution, and the TEOM was used to measure total mass concentration of background aerosol at the upstream sampling station (Fig. 1).

With the exception of five tests, typical average background number concentrations were found to be within 3% of the corresponding downstream average concentrations. In those exceptional cases, the average background concentrations were between 6.1% and 13.9% of the corresponding downstream concentrations. Total background mass concentrations were below 12.4% of the corresponding downstream concentrations, except for four cases, when they were between 20.9% and 37.2% of the corresponding downstream concentrations.

Number concentrations and size distributions. The aerosol number concentrations at the downstream station were continuously measured with the FMPS. The results obtained

Figure 2

Total number concentrations for: (a) M1 and (b) M2 conditions (The data between minute 45 and minute 71 of the muffler test were lost due to power outage).

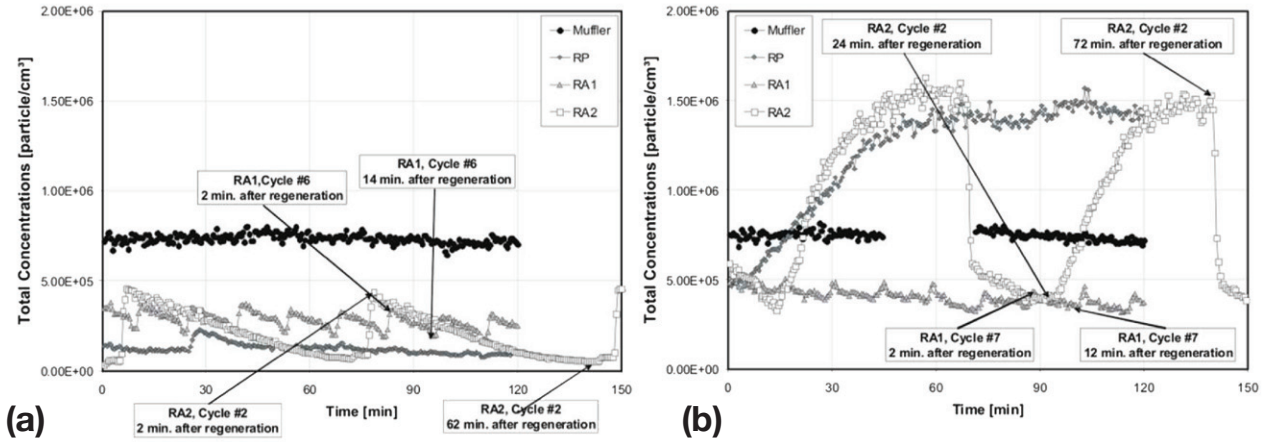


Table 2

Representative parameters for number size distributions of aerosols measured by FMPS.

Exhaust config.	Test mode	Average (time interval) or event (cycle #, minutes after regeneration)	Nucleation mode			Accumulation mode			Nucle.+ Accum.	FMPS meas.
			d_{50}	σ	Total conc.	d_{50}	σ	Total conc.	Total conc.	Total conc.
			Nm	nm	$\#/cm^3[10^4]$	nm	nm	$\#/cm^3[10^4]$	$\#/cm^3[10^4]$	$\#/cm^3[10^4]$
Muffler	M1	Avg., 90-120 min.	12.9	1.30	6.20	49.0	1.54	65.33	71.53	71.54
	M2	Avg., 90-120 min.	16.8	1.51	11.83	54.8	1.50	60.80	72.62	73.17
	M3	Avg., 90-120 min.	—	—	—	52.6	1.62	41.49	41.49	42.27
Rypos Passive (RP)	M1	Avg., 90-120 min.	13.1	1.27	3.05	25.2	1.97	6.57	9.62	9.63
	M2	Avg., 90-120 min.				13.1	1.37	140.30	140.30	144.98
	M3	Avg., 90-120 min.	12.8	1.30	2.50	40.9	1.88	2.32	4.82	4.82
Rypos Active 1 (RA1)	M1	#6, 2	14.4	1.37	3.45	48.5	1.54	30.62	34.07	34.10
		#6, 14	14.1	1.37	3.33	47.1	1.55	16.42	19.75	19.80
	M2	#7, 2	10.6	1.31	13.31	54.3	1.61	25.34	38.64	38.60
		#7, 12	10.2	1.30	16.12	54.0	1.61	20.11	36.22	36.10
	M3	#7, 2				51.4	1.65	15.34	15.34	15.50
		#7, 14				45.5	1.68	4.91	4.91	5.03
Rypos Active 2 (RA2)	M1	#2, 2				47.4	1.55	39.69	39.69	40.70
		#2, 62				53.5	1.57	4.91	4.91	5.29
	M2	#2, 24	10.2	1.29	22.13	53.7	1.59	18.40	40.53	40.40
		#2, 72	15.9	1.43	139.85	44.5	1.78	7.54	147.39	153.00
	M3	#2, 2				53.0	1.58	23.59	23.59	24.10
		#2, 62				46.3	1.62	1.89	1.89	1.97

for the DPF system operated in passive configuration (RP), time-driven active configuration (RA1) and exhaust back pressure-driven active configuration (RA2) were closely examined. Examples of total number concentration traces observed during the tests conducted for M1 and M2 are shown in Figs. 2a and 2b, respectively. The presented concentrations are actual values measured at prevailing ventilation conditions.

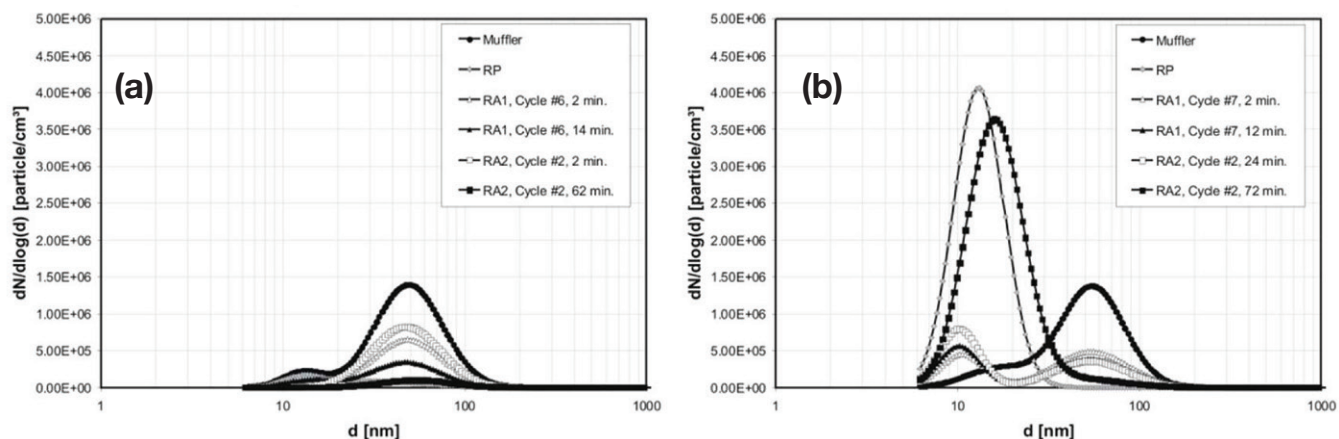
Number concentrations of aerosols at the downstream station were found to be strongly affected by the exhaust

configuration, engine operating conditions and regeneration strategy (Figs. 2a and 2b). The concentrations were found to be relatively uniform during muffler runs and during the later stages of RP runs. When the system was operated in active configurations (RA1 and RA2), the concentrations exhibited transient and cyclic nature. The changes in concentration correlated with regeneration events.

In the case of M1 (Fig. 2a) and M3 conditions, the number concentrations for the system in all three configurations were always substantially lower than those measured in the

Figure 3

Number size distributions for (a) M1 and (b) M2 conditions.



muffler configuration. When the engine was operated over M2 conditions, the total number concentrations during the majority of RP and RA2 tests were substantially higher than those observed during the muffler test (Fig. 2b). The increase in total and overall high number concentrations for RP and RA2 can be primarily linked to a gradual increase in concentrations of nucleation aerosols as DPM built up inside the DPF media. The concentrations peaked at the later stage of the RP test and at the later stage of each of the RA2 regeneration cycles. During DPF operation in RA1 configuration, the number concentrations were always substantially lower than those measured for the muffler (Fig. 2b).

The distributions for the muffler and the later stages of RP tests exhibited a steady nature. Therefore, those were examined as the averages of the distributions measured during the second half of the second hour of the measurement periods. Since the distributions for RA1 and RA2 exhibited a transient nature, they were examined as discrete representative events shown in Figs. 2a and 2b. The distributions were not corrected for background concentrations and/or adjusted for prevailing dilution ratios.

The measured and averaged number size distributions of aerosols were fitted with log-normal curves using DistFit software from Chimera Technologies (Forest Lake, MN). The calculated number median electrical mobility diameters ($_{50}d_{em}$), standard deviation of number distributions (σ), and total number concentrations for both nucleation and accumulation modes for downstream distributions are summarized in Table 2. The total concentrations for fitted and measured distributions, given in the last two columns of Table 2, show an excellent agreement between fitted and actual distributions.

The size distributions for M1 and M2 conditions are shown in Figs. 3a and 3b, respectively.

When the engine was operated at M1 conditions, with a muffler, with the DPF system in passive and time-driven active configurations, the distributions were found to be bimodal, with a pronounced accumulation mode and a slight, but distinctive, nucleation peak (Table 2 and Fig. 3a). For M1 and the DPF system in the RP configuration, the aerosols were found to be exclusively in the accumulation mode. For RA1 and RA2 configurations, the concentrations of aerosols were constantly changing between the regeneration events, and the concentrations of accumulation aerosols were continually dropping with accumulation of DPM in the DPF following the regeneration.

In the cases when the engine was operated at M2 conditions, all size distributions were found to be bimodal (Fig. 3b). In the case when the engine was operated with the muffler, the majority of aerosols were in accumulation mode. On the contrary, for the DPF in RP configuration, at those late stages of the test, the majority of accumulation aerosols were removed by the filter and the distributions were dominated by high concentrations of nucleation aerosols. For RA1 and RA2 configurations, the concentrations of aerosols were continuously changing between and during the regenerations. For RA1 configuration, the concentrations of accumulation aerosols slightly increased with the accumulation of DPM in the DPF. In the case of the RA2 configuration, the concentrations of accumulation aerosols gradually decreased and the concentrations of nucleation aerosols gradually increased between regeneration events, and toward the end of the regeneration cycle the concentrations of both accumulation and nucleation aerosols approached those observed for the DPF operated in RP configuration.

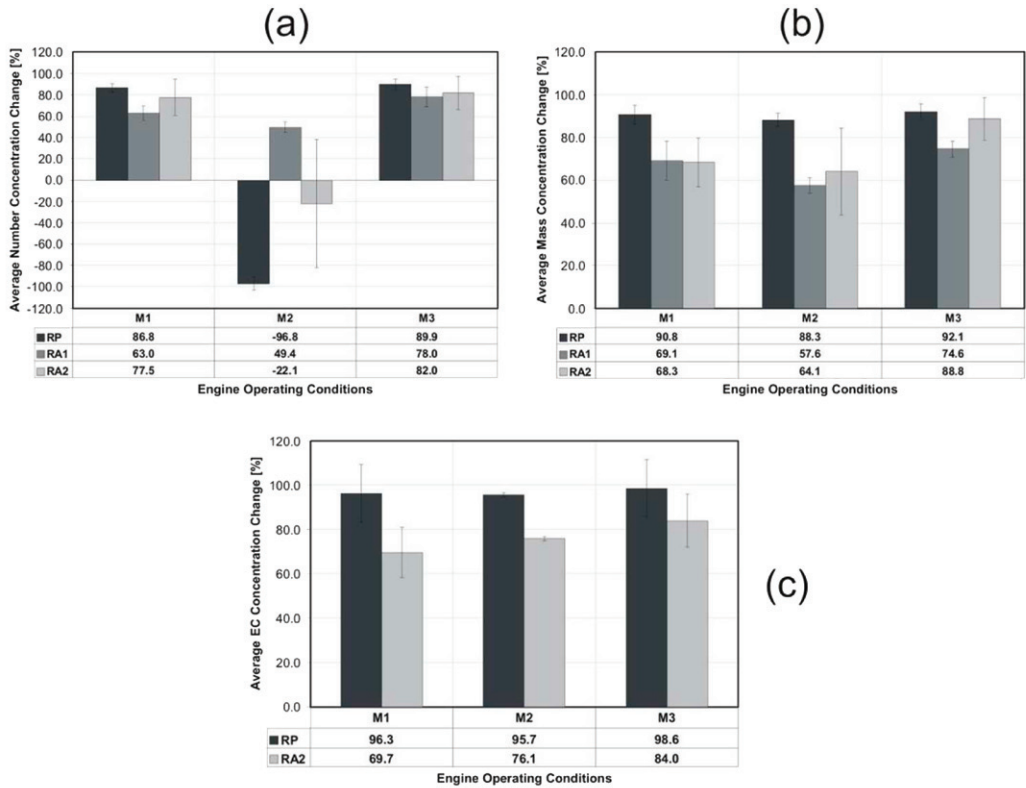
The majority of distributions were single modal when the engine was operated at M3 conditions (Table 2). The exception was the distribution recorded when the system was operated in RP configuration for an extended period of time. In that case, the concentrations of accumulation aerosols dropped to the ambient levels toward the end of the regeneration cycle and a distinctive nucleation mode was apparent. In the case of RA1 and RA2 configurations, the concentrations exhibited a transient nature with a steady decrease in accumulation aerosol concentrations between regeneration events as a function of DPM loading.

In general, aerosol size distributions were found to be affected not only by engine operating conditions and exhaust configuration, but also by the DPF regeneration process. At light load conditions, the distributions were dominated by accumulation mode for all exhaust configurations and regeneration strategies. High concentrations of nucleation aerosols were observed when the test engine, fitted with this DPF that was not catalyzed but had lightly catalyzed DOC attached to its end, was operated at high load conditions.

These results are in agreement with results of previous evaluations of uncatalyzed ceramic and sintered metal DPF systems conducted with the same engine and under similar conditions (Bugarski et al., 2008; Bugarski et al., 2009). A dramatic increase in nucleation mode and disappearance of accumulation mode was observed for high load conditions.

Figure 4

The effects of the regeneration cycle on (a) number concentrations (reduction is positive change), (b) total mass concentrations and (c) average elemental carbon (EC) concentrations.



This behavior is qualitatively consistent with the findings of other researchers (Bugarski et al., 2008; Skillas et al., 2000). A decrease in the accumulation mode reduces potential adsorption sites and scavenging of particle precursors, thus promoting nucleation, while at the same time decreasing coagulation of nucleation mode aerosols with accumulation mode aerosols (Biswas et al., 2008; Jung et al., 2005). Since the engine was fueled with a 10 ppm sulfur fuel and the DOC was relatively lightly catalyzed, possible sulfate formation was expected to be minor (Vaaraslahti et al., 2004) and nucleation mode aerosols were probably primarily made of hydrocarbons. The positive correlation between DPM loading and efficiency has been observed by other researchers (Jung et al., 2005; Lorentzou et al., 2008).

Integrated concentrations

The results of the FMPS measurements at the downstream station and the SMPS measurements at the upstream station were used to calculate the effects of the DPF configurations on integrated aerosol concentrations. The effects of the system on integrated aerosol and EC mass concentrations were assessed using the results of continuous measurements with a TEOM and carbon analysis performed on the samples collected at both the downstream and upstream stations, respectively.

In the cases when the engine was operated with the muffler and the DPF system in RP configuration, the mass concentrations were found to be relatively steady during the second hour of each measurement session. The concentrations were transient and cyclic in nature when the system was operated in RA1 and RA2 configurations. Therefore, for

muffler and RP cases, the average total number and mass concentrations were calculated for the second half hour period of the second hour of each measurement session. For RA1 and RA2 modes, the average total number and mass concentrations were calculated using averages for carefully selected periods that corresponded to regeneration cycles. The averaging periods for RA1 and RA2 tests were four and one regeneration cycle long, respectively. The background corrections were made using cor-

responding averages of concentrations measured at the upstream station. The calculations were made with actual concentrations at the prevailing ventilation conditions and were not normalized with respect to differences in dilution between engine operating conditions.

When operated in passive and both active modes, the system reduced total number concentrations for M1 and M3 conditions (Fig. 4a). The highest average reductions for those conditions were observed when the system was operated in RP configuration. The increase in total number concentrations was observed when the system was operated in RP and RA2 configurations at M2 conditions. For those configurations, the large increases in number of nucleation mode particles resulted in an overall increase in total number concentrations over the muffler case.

The DPF system reduced total mass concentrations for all modes and regeneration schemes (Fig. 4b). The highest reductions in mass concentrations were observed for RP configuration. It appears that in the majority of cases, the average reductions were directly and positively related to the length of regeneration cycle and accumulation of DPM in the DPF.

The elemental carbon (EC) analysis of the upstream samples showed undetectable levels of EC in the background air and, therefore, background correction of EC data was not necessary. Therefore, the results of EC analysis performed on the downstream samples were used to calculate the average EC removal efficiencies for RP and RA2 configurations shown in Fig. 4c. The DPF system reduced EC concentrations for all engine operating conditions and both regeneration schemes. The reductions were substantially higher for the RP than for the RA2 configuration.

Conclusion

The evaluated DPF system was found to be effective in reducing total aerosol and EC mass concentrations in mine air for all engine operating conditions and, potentially, can be used to reduce exposures of underground miners to these pollutants. However, when operated at high-load engine operating conditions, the engine with the evaluated DPF system was found to contribute considerably to the number of nucleation mode aerosols in the mine air. Further, the regeneration process and strategy had a major impact on the DPF system performance. The reductions in mass and EC were higher in passive than in active regeneration configurations. The length of the DPF regeneration cycle and DPM load in the filter had a pronounced effect on the mass and number concentrations and potentially on chemical composition of aerosols in the mine air. An extension in the length of the regeneration cycle resulted in a much larger overall reduction of total DPM and EC mass concentrations for all test conditions, but also produced higher concentrations of nucleation aerosols for high engine load conditions. The results indicate that the regeneration process might be optimized to maximize mass reductions and minimize formation of nucleation aerosols.

It is important to note that the reported results are specific to the type of DPF system evaluated in this study and that the other types of DPF systems might have different effects on concentrations and size distribution of aerosols emitted by diesel engines. For analytical reasons, the testing was done for selected steady-state engine operating conditions. In order to better understand the effects of these processes on diesel aerosols in actual underground mines, it would be necessary to evaluate the role of these processes for transient engine and vehicle operating conditions.

The findings of this study underline the importance of comprehensive evaluation of the effects of complex exhaust aftertreatment devices such as DPF systems on the physical, chemical and toxicological properties of diesel aerosols and their potential as a control strategy for reducing risks associated with exposure of workers to diesel aerosols.

Disclaimer

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