FIELD AND LABORATORY EVALUATION OF A SINTERED METAL DIESEL FILTRATION SYSTEM

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ABSTRACT

A series of field and laboratory evaluations were conducted in order to characterize the effects of a Mann+Hummel SMF-AR® diesel particulate filter (DPF) system on the aerosols and criteria gases emitted by diesel engines. This system, with a durable sintered metal filter media and available active regeneration via an on-board electrical heater, has been considered for retrofitting diesel engines used in light- and medium-duty underground mining applications. Two DPF systems were installed on a forklift and locomotive from the underground mining fleet of the Vale's Creighton Mine and evaluated over a 1,500-hour trial. This evaluation was complemented with field and laboratory emissions tests. The field tests were performed on the vehicles while at the Creighton Mine surface shop. During those tests, the emissions were assessed for the engines operated at hydraulic stall, high idle, and low idle conditions. The laboratory tests were executed at the diesel engine emissions laboratory at the National Institute for Occupational Safety and Health (NIOSH), here the DPF removed from the forklift was further evaluated at four steady-state engine operating conditions as well as at transient conditions using a custom-designed duty cycle. Very similar methodologies were used during field and laboratory tests to measure concentrations of aerosols and criteria gases in the diesel exhaust, both upstream and downstream of the DPF system. The concentrations and size distributions of aerosols were measured using a fast mobility particle sizer spectrometer, in exhaust diluted by a partial flow dilution system. The concentrations of CO_2, CO, NO, and NO_2 were measured in the raw exhaust using a Fourier transform infra-red spectrometer. Both field and laboratory emissions tests showed that the evaluated DPF systems were very effective in reducing aerosol emissions from all tested engines, and for all test conditions. The systems were found to have minor effects on gaseous emissions from those engines. The findings from this study should help the mining industry to better understand the benefits and challenges of using DPF systems to control the exposure of underground miners to diesel aerosols.

KEYWORDS

Diesel, Particulate filter systems, Aerosols, Gases

INTRODUCTION

Extensive research conducted at various underground mining operations and laboratories over the past few decades (Stachulak et al., 2005 & 2012; Bugarski et al., 2009 & 2012) showed that retrofit-type diesel particulate filter (DPF) systems are very effective as a control technology for reducing the exposure of underground miners to aerosols emitted by diesel-powered vehicles. The long-term studies conducted at Vale operations (Stachulak et al., 2005 & 2012) identified several types of DPF systems suitable for heavy-duty applications and the need for additional work on investigating potential solutions for light-duty applications. To further investigate the issues related to light-duty applications, Vale conducted a long-term evaluation of the hybrid (passive/active) DPF system from a Mann+Hummel GMBH (M+H) (Speyer, Germany, Model SMF-AR®) (Stachulak & Hensel, 2010). A durable sintered metal filter media and the regeneration of the filter media (carried out by an on-board electrical heater and supported by iron-based fuel additives) make this system attractive for retrofitting diesel engines used in light- and medium-duty underground mining applications. The operational, durability, and reliability issues were studied by monitoring performance of the systems installed on two light-duty vehicles from the diesel fleet at the Creighton Mine in Sudbury, Ontario, for over 1,500 hours. In order to quantify the performance of the systems, the long-term evaluation was complemented with the field and laboratory emissions tests described in this manuscript.

METHODOLOGY

Two similar M+H SMF AR DPF systems were installed and evaluated on two light-duty vehicles, a forklift and locomotive as described in Table 1. The laboratory evaluation was conducted using the DPF system that was initially evaluated long-term on the forklift and subsequently installed on the NIOSH dynamometer coupled with the Isuzu C240 engine (Table 1). The systems were designed using filtration elements built with sintered material with 10-μm mean pore size, 45% porosity, and 0.38-mm wall thickness.

Table 1 – Test vehicles and engines

Test Vehicles	Forklift	Locomotive	Dynamometer
Vehicle/Dynamometer Manufacturer and Model	Kubota R520SF	Clayton Equipment Ltd. 10-ton loco.	SAJ SE150
Engine Manufacturer	Kubota	Deutz Corp.	Isuzu
Engine Model	V2203-M-ES	F6L912W	C240
Number of Cylinders	4 (inline)	6 (inline)	4 (inline)
Engine Displacement	2.2 l	6.1 l	2.4 l
Engine Type	liquid cooled, naturally aspirated	air cooled, naturally aspirated	liquid cooled, naturally aspirated
Engine Output	36 kW (49 hp)	60 kW (80 hp)	41.8 KW (56 hp)

With respect to regeneration concept, this type of DPF system is considered to be a hybrid. The system is regenerated passively when the vehicle/engine duty cycle provides an adequate sustained temperature and the energy needed to initiate and support the regeneration process. When needed, the active regeneration could be provided using on-board electrical heaters (Figure 1**Error! Reference source not found.**). Both passive and active regenerations are facilitated by use of an iron-based fuel-borne catalyst (FBC) manufactured by Innospec Ltd. (Cheshire, U.K., Satacene®) and marketed by M+H as DT8i. More details on design, operation of the system, and functionality of the catalyst are available from Stachulak and Hensel (2010).

The field emission tests were performed on the vehicles parked in a surface maintenance shop at Creighton Mine. The emissions of tested vehicles/engines were assessed for three steady-state engine operating conditions summarized in Table 2. At high idle (HI) and low idle (LI) conditions the engines in the test vehicles were not additionally loaded. Under hydraulic stall (HS) condition, the engine was loaded against the variable displacement hydraulic pumps. The engines in the forklift and locomotive were fueled using a single-batch of ultralow sulphur diesel (ULSD) fuel from a main mine supply The catalyst was added to the fuel at a 1.65-ml/l rate using an on-board dosing system installed on each of the tested vehicles.

The limited-scope field tests were complemented with the extensive laboratory tests conducted at the diesel laboratory at the Office of Mine Safety and Health Research Laboratory (OMSHR), part of the National Institute for Occupational Safety and Health (NIOSH). The test engine was exercised over four steady-state (Table 3) and one transient (TR) (Figure 2) engine operating cycle using the water-cooled eddy-current dynamometer (Table 1). The transient cycle was designed to simulate the duty cycle of engines used in underground mining operation in the Creighton Mine. The 988-second cycle was repeated multiple times during several-hour long tests. During laboratory tests, the test engine was fuelled with ULSD fuel obtained from a local supplier and doped with the DT8i catalyst (1.65 ml/l). In the laboratory, the fuel/additive mixture was prepared prior to the tests by adding the catalyst to the main supply tank.

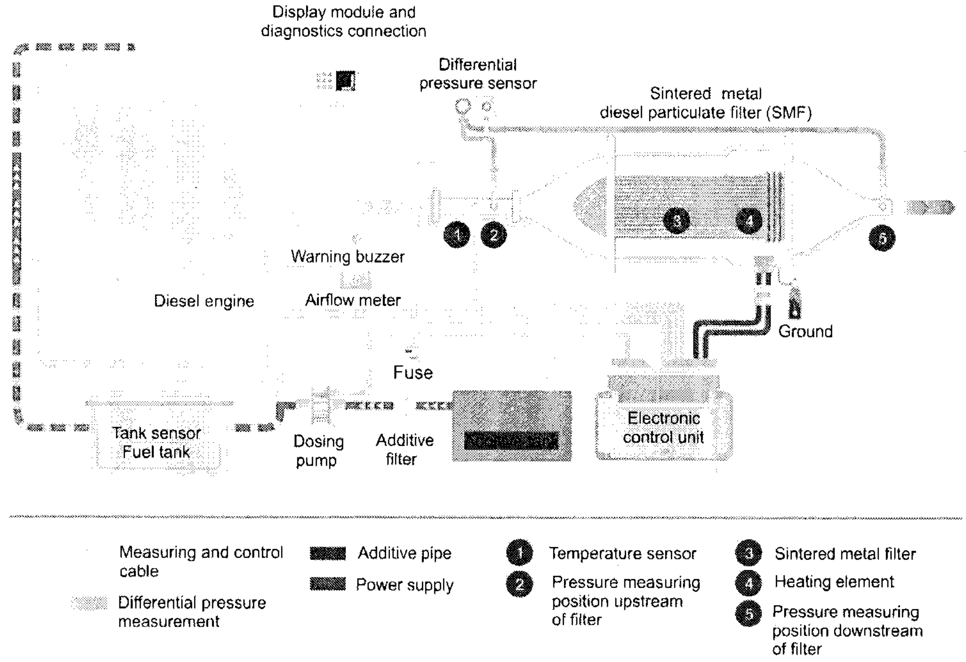


Figure 1 – Mann+Hummel SMF AR system layout

Table 2 – Vehicle/engine operating conditions for field tests

Conditions	Forklift/Kubota V2203-M-ES	Locomotive/Deutz F6L912W
Hydraulic Stall (HS)	2160 rpm	2600 rpm
High Idle (HI)	2240 rpm	2900 rpm
Low Idle (LI)	760 rpm	700 rpm

The measurements were performed in the samples drawn from the exhaust system sequentially from the ports located upstream (engine-out, EOut) and downstream (filter-out, FOut) of the DPF systems. Aerosol concentrations and size distributions were measured in a diluted exhaust with a Fast Mobility Particle Sizer™ (FMPS™) spectrometer from TSI, Inc. (St. Paul, Minn.) (Johnson et al., 2004). In both the field and laboratory studies, the exhaust was diluted using the same two-stage partial dilution system, Dekati FPS 4000 ("Fine Particle Sampler", 2009). The nominal total dilution rates (DRs) of 110:1 (EOut) and 70:1 (FOut) were used in the field study, and 30:1 was used for the laboratory study. The primary dilution was accomplished via a perforated tube diluter and the secondary dilution was accomplished via an ejector-type diluter ("Fine Particle Sampler", 2009). A residence time chamber was inserted between the primary and secondary diluters to allow enough time for nucleation and growth of aerosols (Mathis et al., 2004; "Fine Particle Sampler", 2009). The dilution ratios used in this study are comparable to those achieved when exhaust is diluted by ambient air using MSHA-recommended ventilation rates ("61 Fed. Reg. 55411", 1996). The concentrations of carbon dioxide (CO_2), carbon monoxide (CO), nitric oxide (NO), and nitrogen dioxide (NO_2) were measured in raw (undiluted) exhaust drawn from the upstream and downstream exhaust ports using a Fourier Transform Infra-Red (FTIR) spectrometer (Gasmet 4000-SYS).

Table 3 – Steady-state operating conditions used for laboratory tests

Conditions	Description	Engine Speed Rpm	Torque Nm	Power kW
R50	Rated speed and 50% load	2950	55.6	17.2
R100	Rated speed and 100% load	2950	111.2	34.3
I50	Intermediate speed and 50% load	2100	69.1	14.9
I100	Intermediate speed and 100% load	2100	136.9	30.6

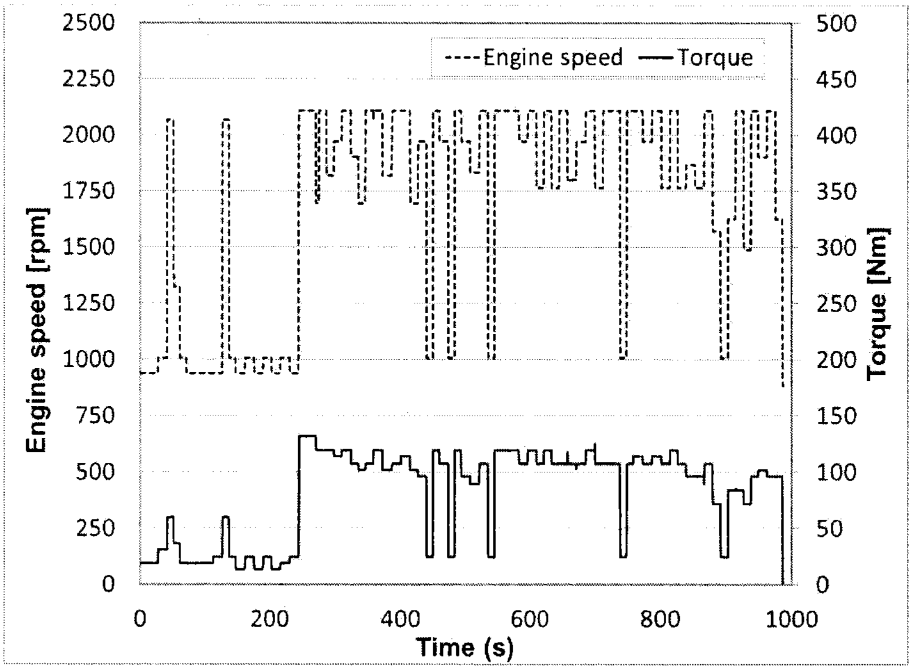


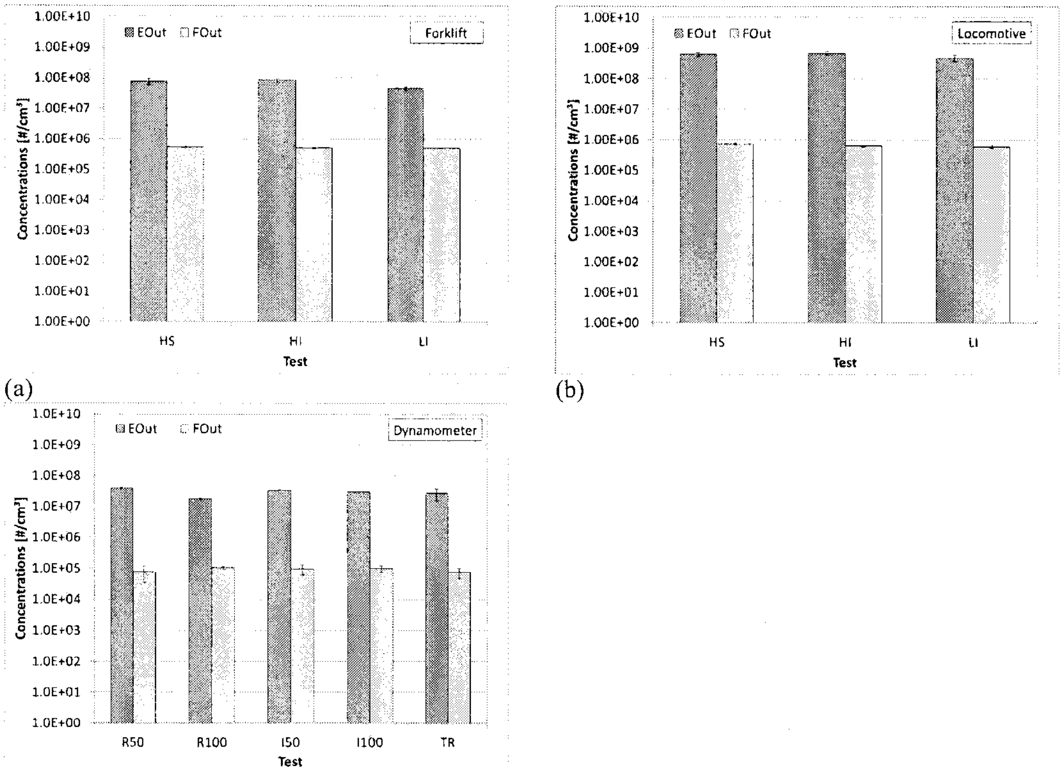
Figure 2 – Transient cycle used during laboratory evaluation

The results of measurements performed upstream and downstream of the systems installed on the forklift, locomotive, and test engine connected to the dynamometer were used to assess the net effects of the DPF systems on aerosol and gaseous emissions. Eighteen sequential measurements were performed in the exhaust of the forklift and locomotive. Triplicate measurements were executed for each combination of the sampling location (EOut and FOut) and three test conditions. The mean concentrations were calculated using results gathered during the last minute of the two-minute hydraulic stall tests and the last minute of the four-minute high/low idle tests. During the dynamometer tests, the concentrations were continuously measured for all four steady-state and for transient operating cycle condition of at least two hours. The analysis was performed on the results obtained for the last hour of each of those tests.

RESULTS

Effects of the Systems on Aerosol Concentrations and Size Distributions

The mean total aerosol number concentrations calculated using the results of the particle sizer measurements performed upstream and downstream of the tested DPF systems are summarized in Figure 3. The presented concentrations were corrected using corresponding test-specific mean dilution rates. The positive and negative error bars represent the standard deviations of means.



(a)

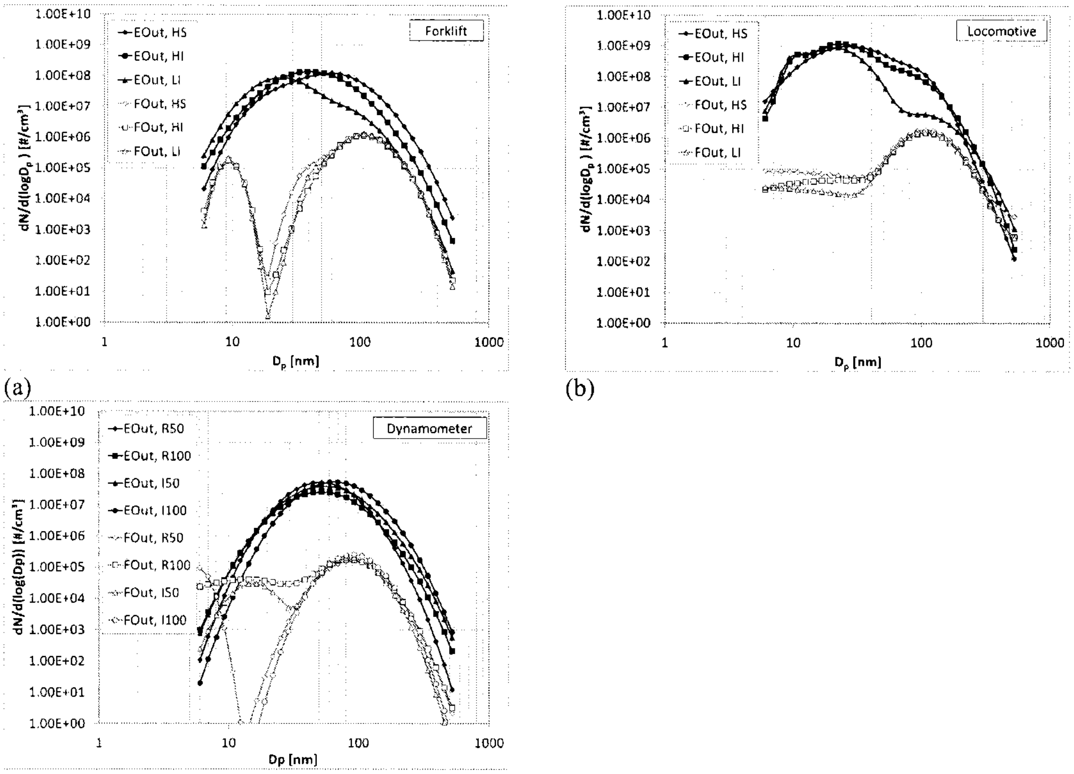
(b)

(c)

Figure 3 – Mean total aerosol number concentrations in the exhaust upstream (EOut) and downstream (FOut) of the DPF systems installed on the (a) forklift, (b) locomotive, and (c) engine coupled to dynamometer.

The results show that the mean total aerosol number concentrations measured downstream of the DPF systems installed on the forklift, locomotive, and Isuzu C240 engine were more than 99% lower than the corresponding concentrations measured upstream of the DPF systems. Furthermore, the laboratory test shows that the FOut concentrations were not affected by engine operating conditions.

The dilution corrected count size distributions of aerosols measured upstream (EOut) and downstream (FOut) of the DPF systems installed for the second runs of stall and idle tests for the forklift and locomotive engines , and for the steady-state tests of the engine coupled to the dynamometer are shown in Figure 4. The measured distributions were fitted with log-normal curves using DistFit software from Chimera Technologies. The statistical parameters including count median diameter (CMD), standard deviation of mean (σ), and total number concentrations (TC) for those number size distributions are given in Table 4**Error! Reference source not found.**.



(a) (b) (c)

Figure 4 – Selected dilution corrected count size distributions of aerosols measured with FMPS upstream (EOut) and downstream (FOut) of DPF systems installed on the (a) forklift, (b) locomotive, and (c) engine coupled to the dynamometer

From the forklift field tests, the count size distributions of aerosols emitted by the engine (EOut) were found to be unimodal or bimodal (Figure 4a and Table 4). For hydraulic stall and high idle conditions (HS & HI), the majority of each EOut aerosol was distributed in the accumulation mode with average CMDs of 59 and 41 nm, respectively. For the low idle (LI) conditions, the majority of the engine exhaust aerosol was found in nucleation mode with a count mean diameter (CMD) of 24 nm. For the same vehicle, while the after filter (FOut) size distributions during field testing were either bimodal or trimodal, depending on engine operating conditions, all were distributed in accumulation mode with average mean diameters between 106 and 109 nm. The after filter aerosol distributions were also characterized with pronounced nucleation peaks with mean diameters of 9 nm.

From the locomotive field tests, depending on engine operating conditions, the count size distributions of aerosols emitted by engine were either bimodal or trimodal (Figure 4b and Table 4), and under all three test conditions, the majority of the aerosols were distributed in the nucleation mode with average count mean diameters ranging from 10 to 27 nm. After the DPF system installed on the locomotive, all the aerosol size distributions were bimodal, and the majority of each aerosol was in the accumulation mode with average mean diameters between 107 and 108 nm. These after filter distributions, similar to the forklift, were also characterized by noticeable nucleation peaks with mean diameters between 3 and 22 nm.

From the laboratory dynamometer testing, for all four steady-state conditions, the count size distributions of aerosols emitted by the Isuzu C240 engine (EOut) were found to be unimodal with CMDs between 52 and 66 nm (Figure 4

Figure 4c and Table 4). After the DPF, the size distributions were bimodal for all but the intermediate speed full load condition where it was unimodal, and all aerosols were in the accumulation modes with mean diameters ranging between 85 and 91 nm.

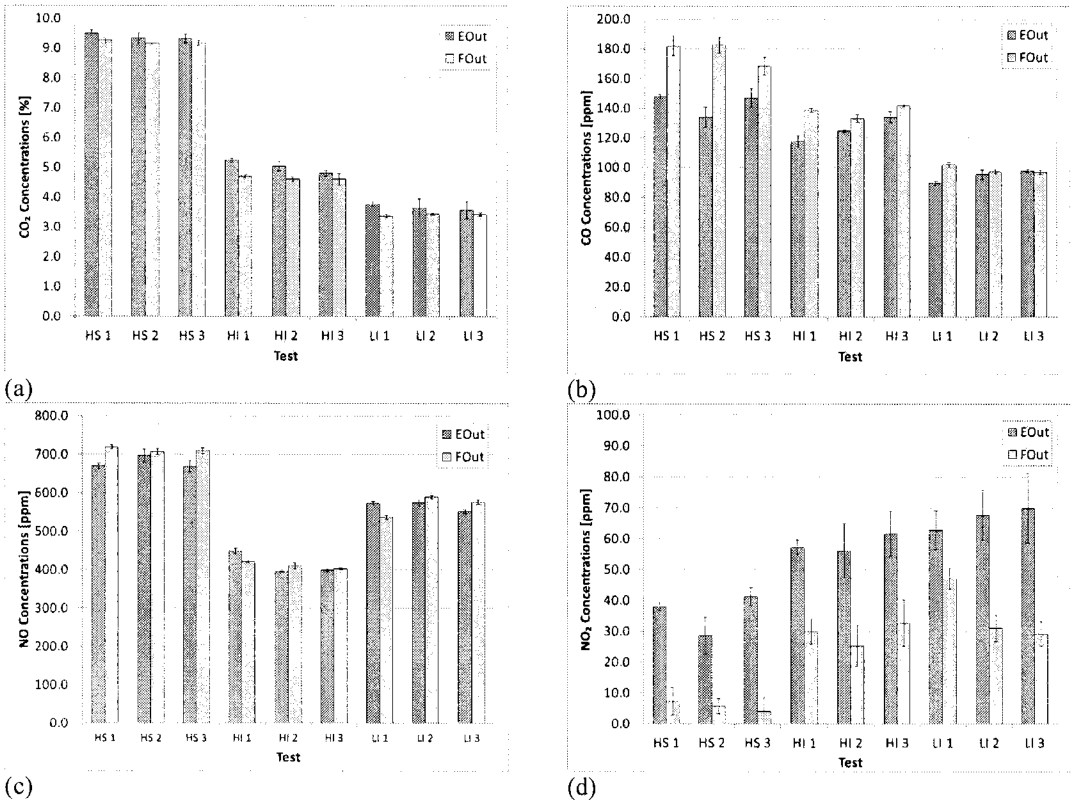


Figure 5 – Engine-out (EOut) and filter-out (FOut) concentrations of (a) CO_2, (b) CO, (c) NO, and (d) NO_2 in undiluted exhaust of the forklift for three runs conducted at HS, HI, and LI conditions

Effects of the systems on CO_2, CO, NO, and NO_2 concentrations

Since the tested DPF system had negligible effects on CO_2 concentrations, the CO_2 results could be used to examine the validity of the test procedures. The CO_2 results (Figures 5a, 6a and 7a) showed very good repeatability of the engine test conditions sufficient to warrant direct comparison of the results of emission measurements performed for corresponding conditions and locations, but at different instances. The relatively high concentrations of CO_2 in the exhaust of the engines in the forklift (**Error! Reference source not found.**a) and locomotive (

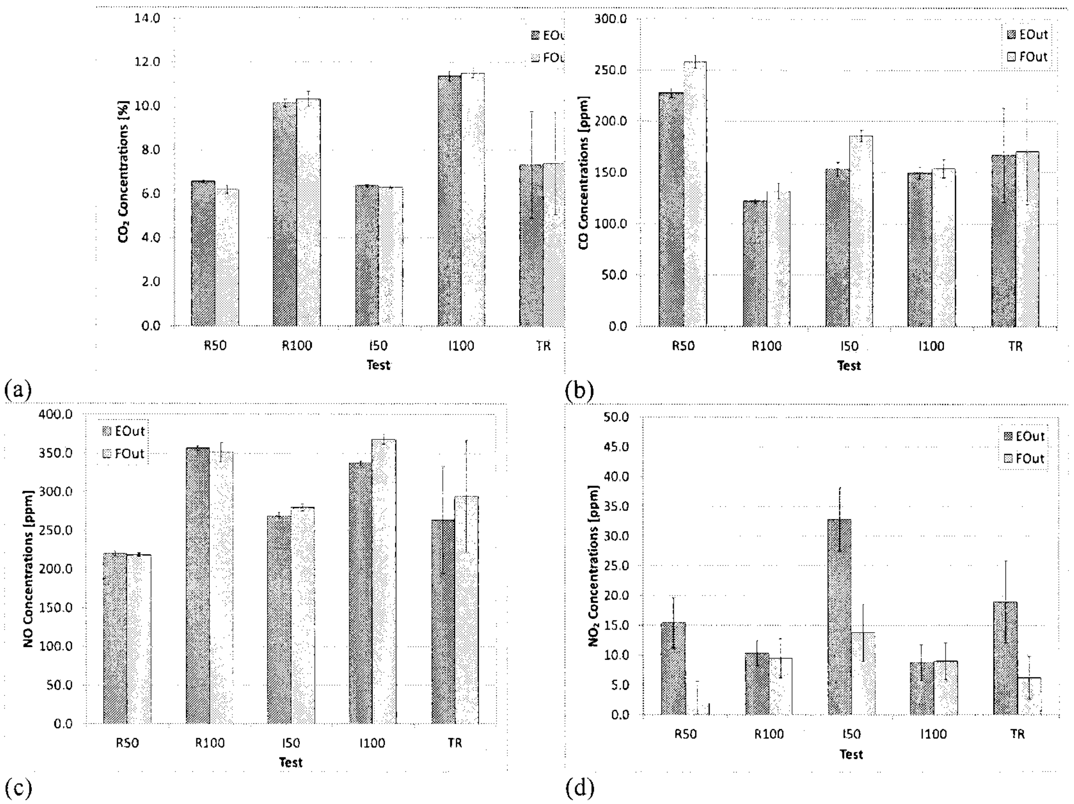
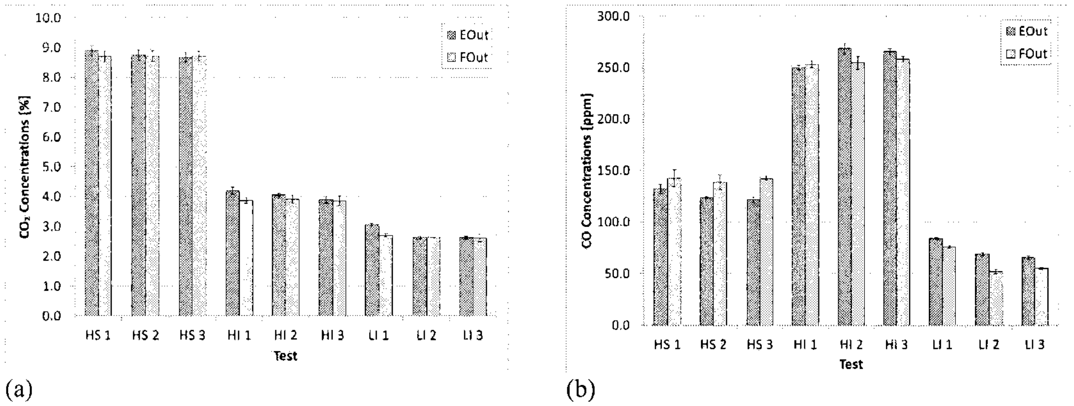
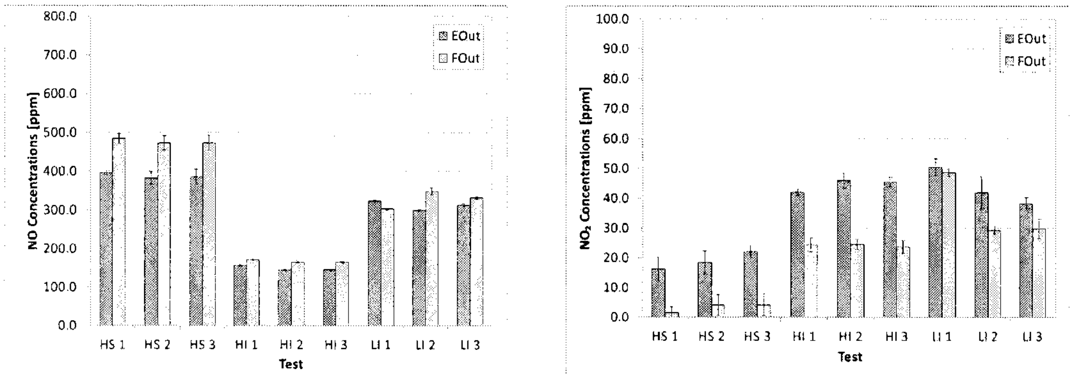


Figure 7 – Engine-out (EOut) and filter-out (FOut) concentrations of (a) CO2, (b) CO, (c) NO, and (d) NO2 in undiluted exhaust of the Isuzu C240 engine for four steady-state (R50, R100, I50, and I100) conditions and one transient condition (TR)

a) indicate that the hydraulic stall (HS) conditions produced fairly high loads on those engines.

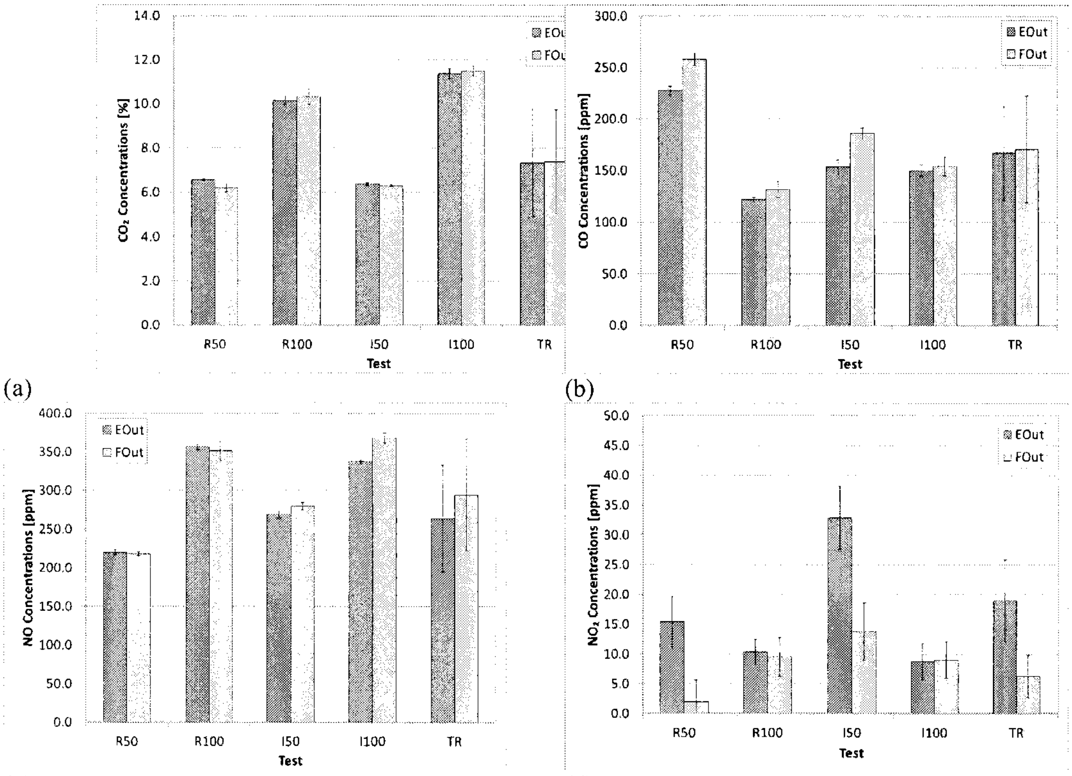




(c) (d)

Figure 6 – Engine-out (EOut) and filter-out (FOut) concentrations of (a) CO_2, (b) CO, (c) NO, and (d) NO_2 in undiluted exhaust of the locomotive for three runs conducted at HS, HI, and LI conditions

In general, the effects of the tested DPF systems on CO emissions were found to be relatively minor. In a number of the cases the effects were within accuracy limits of the measurement method. In the case of the hydraulic stall condition, the higher after filter CO emissions (**Error! Reference source not found.**b and



(a) (b)

(c) (d)

Figure 7 – Engine-out (EOut) and filter-out (FOut) concentrations of (a) CO2, (b) CO, (c) NO, and (d) NO2 in undiluted exhaust of the Isuzu C240 engine for four steady-state (R50, R100, I50, and I100) conditions and one transient condition (TR)

b) could potentially be explained by spontaneous regeneration events of the DPF elements as supported by the relatively high exhaust temperatures, 400°C for the forklift and 450°C for the locomotive, detected at those conditions.

The effects of the systems on total NO_X ($NO+NO_2$) emissions were found to be relatively minor. However, the fractions of NO and NO_2 in NO_X varied substantially with engine operating conditions and potentially with the amount of soot accumulated in the filter elements (Figures 5c, 5d, 6c, 6d, 7c & 7d). In a number of the tests, the concentrations of NO were slightly, but measurably higher downstream than upstream of the systems. The observed changes in NO concentrations inversely correlated with corresponding changes in NO_2 concentrations. For the majority of field and laboratory test conditions there were reductions in NO_2 concentrations across the filter which can be potentially attributed to the reaction of NO_2 with soot captured in the DPF elements. However, it appears that this process was not prominent for rated and intermediate speed tests at full load (R100 & I100) conditions that generated relatively high exhaust temperatures (>400 °C) sufficient to supported continuous regeneration of the DPF elements (as indicated by backpressure results). The differences in NO and NO_2 might be also partially attributed to the differences in exhaust gas temperatures at the two sampling locations.

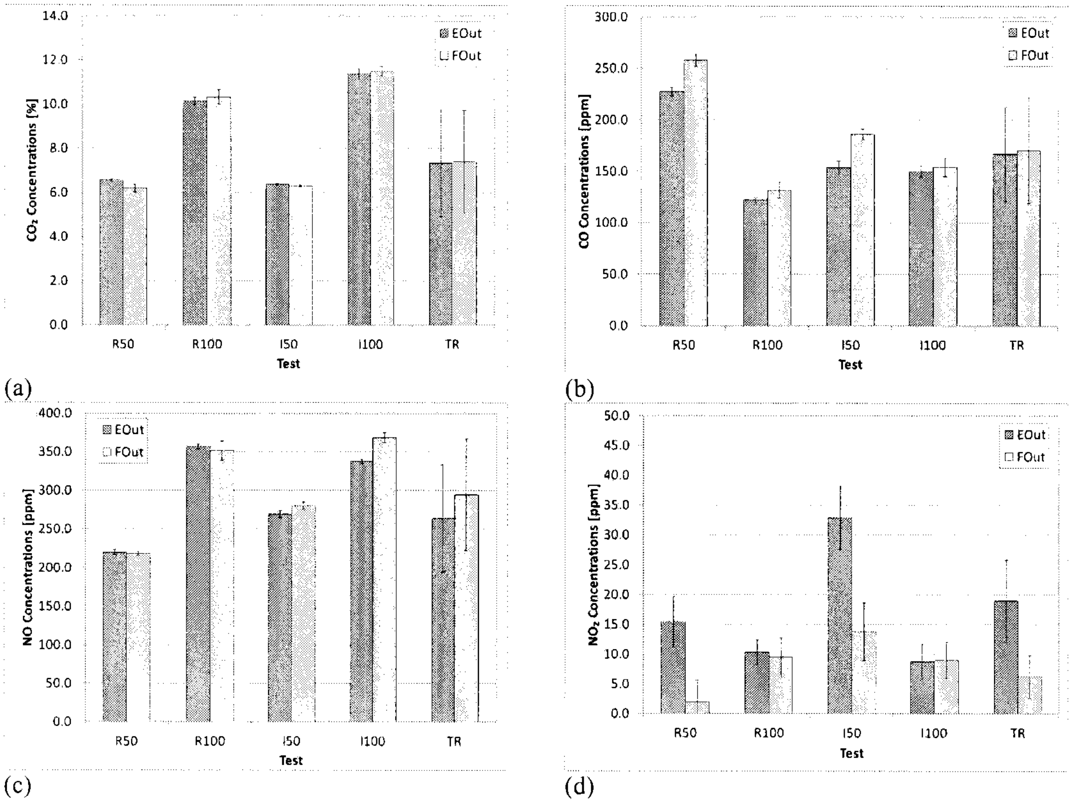


Figure 7 – Engine-out (EOut) and filter-out (FOut) concentrations of (a) CO_2, (b) CO, (c) NO, and (d) NO_2 in undiluted exhaust of the Isuzu C240 engine for four steady-state (R50, R100, I50, and I100) conditions and one transient condition (TR)

CONCLUSIONS

The field and laboratory tests showed that the evaluated DPF systems were very effective in reducing total number concentrations of aerosols emitted from all three diesel engines tested. For all test conditions, the tested DPF system removed more than 99% of the aerosols count. The slight test-to-test differences in theoretical efficiency numbers were primarily traced to the engine and operating conditions producing differences in engine-out concentrations. The reductions in concentrations were observed for almost the complete range of aerosol sizes. However, the relatively large fractions of aerosols which remained downstream of the tested DPF systems were found to be nucleation aerosols whose properties warrant further investigation. The effects of the DPF systems on CO_2, CO, and NO emissions were found to be relatively minor. The NOx concentrations downstream of the tested DPF systems were found to be lower than the corresponding NOx concentrations emitted by the test engines in almost all cases. The results of this study are in good agreement with the results of the previous evaluation of a similar DPF system at similar test condition in an experimental mine (Bugarski et al., 2008). The findings from this study and long-term evaluation at Creighton Mine (Stachulak & Hensel, 2010) showed that the evaluated sintered metal DPF systems is a viable control technology that can be used to substantially reduce exposure of underground miners to aerosols emitted by light-duty diesel-powered vehicles.

DISCLAIMER

The findings and conclusions of this publication are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health (NIOSH) and Vale. Mention of company names or products does not constitute endorsement by NIOSH.

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Table 4 - Statistical parameters including count median diameter (CMD), standard deviation of mean (σ), and total number concentrations (TC) for the count size distributions shown in Figure 4

Tested System	Measure. Location	Test Mode	Size Distribution Mode 1			Size Distribution Mode 2			Size Distribution Mode 3			TC	
			CMD	σ	TC	CMD	σ	TC	CMD	σ	TC	Fit	Meas.
			nm	-	#/cm^3	Nm	-	#/cm^3	nm	-	#/cm^3	#/cm^3	#/cm^3
Fork-lift	EOut	HS	23.2	1.43	9.4E+6	58.9	1.60	6.2E+7				7.2E+7	7.2E+7
		HI				40.9	1.66	7.7E+7				7.7E+7	7.7E+7
		LI	24.2	1.50	3.9E+7	66.5	1.52	4.0E+6				4.3E+7	4.5E+7
	FOut	HS	9.4	1.16	2.8E+4	45.0	1.23	2.8E+4	108.0	1.400	4.8E+5	5.4E+5	5.4E+5
		HI	9.3	1.17	3.1E+4	106.0	1.41	4.4E+5				4.7E+5	4.7E+5
		LI	9.4	1.15	3.2E+4	45.8	1.15	1.1E+4	109.0	1.390	4.5E+5	4.9E+5	5.0E+5
Loco-motive	EOut	HS	27.2	1.69	5.6E+8	85.6	1.32	3.5E+7				5.9E+8	5.9E+8
		HI	10.5	1.14	4.8E+7	23.0	1.49	5.1E+8	67.4	1.490	5.9E+7	6.1E+8	6.2E+8
		LI	10.1	1.14	5.0E+7	19.9	1.47	3.8E+8	101.0	1.490	2.5E+6	4.4E+8	4.4E+8
	FOut	HS	4.8	6.00	1.7E+5	107.8	1.40	6.8E+5				8.5E+5	7.6E+5
		HI	21.7	2.96	5.1E+4	108.2	1.39	5.6E+5				6.1E+5	6.1E+5
		LI	3.5	6.00	5.2E+4	107.1	1.41	5.6E+5				6.1E+5	6.0E+5
Dynam-ometer	EOut	R50				51.7	1.52	2.5E+7				2.5E+7	2.6E+7
		R100				52.0	1.61	1.4E+7				1.4E+7	1.4E+7
		I50				55.3	1.61	2.1E+7				2.1E+7	2.2E+7
		I100				66.2	1.55	2.7E+7				2.7E+7	2.7E+7
	FOut	R50	5.8	1.17	1.7E+4	89.5	1.45	6.6E+4				8.2E+4	7.4E+4
		R100	13.4	2.23	3.5E+4	84.6	1.47	7.4E+4				1.1E+5	1.1E+5
		I50	15.7	1.36	1.0E+4	86.0	1.40	7.7E+4				8.7E+4	8.7E+4
		I100				90.9	1.40	9.5E+4				9.5E+4	9.7E+4