Protected Business Information

CANMET Mining and Mineral Sciences Laboratories

Performance Evaluation of Diesel Particulate Filter and Oxidation Catalysts

by M. Gangal, B. Rubeli, D. Young,
E. Leung and V. Feres

Work performed for:
Catalytic Exhaust Products Limited

Project: 603664
Report CANMET-MMSL 10-004(CR) *Version: January 2010*

For your convenience we are forwarding an electronic version of the report as part of the official Deliverable for the contract. Please note however that since electronic versions may be altered during or after transmission, should any discrepancies arise between versions, CANMET-MMSL will support only the original bound version of the report maintained at the Business Office of CANMET Mining and Mineral Sciences Laboratories.

Natural Resources Canada Ressources naturelles Canada

Canada

INTRODUCTION

This report contains a summary of emissions data for a Kubota engine model V3307-DI-T, tier 4i, obtained with and without the application of four Catalytic Exhaust Products (CEP) Limited devices for the control of diesel particulate matter (DPM). The devices included three diesel oxidation catalysts (DOCs) and a diesel particulate filter (DPF). The testing was performed at the Diesel Emissions Research Laboratory of CANMET-MMSL, Ottawa. This laboratory is registered to ISO 9001:2000 standards. In addition, the test facility is recognized as an Accredited Testing Laboratory by the Standards Council of Canada to comply with the requirements of ISO/IEC 17025 for specific tests. The engine dynamometer followed ISO 8178-C1 8-mode test cycle protocol and used ultra-low sulphur diesel fuel.

A total of five 8-mode tests were performed for this study including, (1) engine only-baseline, (2) engine with a catalyst, model #SC DOC, (3) engine with a second catalyst model #2G CC, (4) engine with a third catalyst model #5G SXC and (5) engine with a diesel particulate filter model #SC DPF.

For all test cycles, carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), nitric oxide (NO), oxides of nitrogen (NO_x), total hydrocarbons (THC), and diesel particulate matter (DPM) were measured.

For this testing, all three catalysts and the diesel particulate filter were provided by Catalytic Exhaust Products Limited.

EXPERIMENTAL APPROACH

This section provides some information on the test engine, test fuel, and test procedure for the evaluation of the DPM control technologies.

Test Engine

The engine used for the testing was a Kubota engine, model V3307-DI-T, 4 cylinder, turbocharged, EGR, EPA tier 4i engine. Table 1 provides some engine specification data.

Table 1. Test engine specifications

Make	Kubota
Model	V3307-DI-T, tier 4i
Serial number	8A0651
Displacement	3.3 Litre
Rated power, gross	74 hp @ 2600 rpm
Fuel rate at rated power	31.9 lb/hr
Peak torque	195.5 lb.ft @1600 rpm
Peak torque speed	1600 rpm
Aspiration	Turbocharged
Fuel system	DI, mechanically controlled fuel injection
Max exhaust backpressure	61.5" H_2O
Low idle speed	775-825 rpm
High idle speed	2820 rpm

Test Fuel

The diesel fuel used for this study was an ultra-low sulphur diesel fuel with a sulphur value of 11 ppm (CAN/CGSB-3.517-2000). Some of the laboratory analysed fuel properties are given in Table 2.

Table 2. Some diesel fuel properties

Properties	**ASTM test method**	**Analysis**
Specific gravity 60/60F	D4052	0.8248
Density @ 15°C, kg/m^3	D4052	824.1
Carbon, wt%	D5291	86.32
Hydrogen, wt%	D5291	13.94
Nitrogen, wt%	D5291	<0.3
Flash point, °C	D93	54.1
Sulphur, ppm	D7039	10.8

DPM Control Devices

CEP supplied three catalysts and one diesel particulate filter for this study. The devices were tested as supplied, and were de-greened by the client prior to shipping the devices to the laboratory.

Prior to testing, all the devices were mounted within 30 inches from the outlet of the engine turbocharger. The devices were tested in the following order and configurations:

Baseline test	Engine baseline, without any devices (called Baseline Data)
Test 1	Engine plus the catalytic #SC DOC
Test 2	Engine plus the catalytic #2G CC
Test 3	Engine plus the catalytic #5G SXC
Test 4	Engine plus the diesel particulate filter #SC DPF

Test Procedure

The engine exhaust emissions were measured at all modes of the ISO 8178-C1 test cycle. The 8-mode test cycle for the Kubota engine is defined in Table 3. The integrated 8-mode average values for all tests were calculated using the appropriate weighting factors for each mode.

Table 3. ISO 8178-C1 8-mode test cycle

Mode #	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Engine Speed, rpm	2600				1600			785
Torque, %	100	75	50	10	100	75	50	0
Weighting factor	0.15	0.15	0.15	0.1	0.1	0.1	0.1	0.15

Gaseous Emission Measurement

The raw exhaust gas concentrations were measured using a California Analytical Instruments (CAI) gas cart. The gas cart consists of an exhaust gas sampling and conditioning system, emission analysers, 64 point gas divider for system calibration, and NO_x efficiency tester. The gas cart contains the following gas analyzers:

- Low range carbon monoxide (CO), model CAI 100 IR, non-dispersive infrared (NDIR) detection system, span ranges 0-100 ppm and 0-2000 ppm.
- Carbon dioxide (CO_2) and high carbon monoxide (HCO) model CAI 300 IR, non-dispersive infrared (NDIR) detection system, CO_2 span ranges 0-5.0% and 0-20.0%, and CO span range 0-1.0%.
- Oxygen (O_2), model CAI 300 Oxygen, paramagnetic (PMA) detection system, span ranges 0-5% and 0-25%.
- Oxides of nitrogen (NO/NO_x), model CAI 400 HCLD heated, chemiluminescence (CLD) detection system, span ranges 0-1000 ppm and 0-3000 ppm. The gas cart has two NO/NO_x analyzers that provide simultaneous measurements of NO and NO_x. The concentration of NO_2 is determined by the difference of NO_x and NO concentrations.
- Total hydrocarbons (THC), model CAI 300 HFID, heated flame ionization detector (HFID), span ranges 0-100 ppm and 0-1000 ppm.

Particulate Measurement

The Diesel Particulate Matter (DPM) was measured gravimetrically using a Sierra BG-2 particulate partial flow sampling system. This is a fully automated test stand with a micro-dilution chamber which draws a sample of exhaust gas directly from the engine exhaust stack and dilutes the entire sample fraction. The system's two mass flow controllers provide the required control of flow rates and dilution ratios.

The particulate sample is collected on dual Pallflex T60A20 (Teflon coated glass fibre) 90-mm filters. All filters are conditioned in an environmentally controlled balance room with air conditions of 22 ± 3°C temperature and at 45 ± 8% relative humidity for at least one hour before weighing. After conditioning, the filters are weighed and placed in stainless steel filter holders. After particulate sample collection using the BG2 micro-dilution system, the filters were returned to the controlled balance chamber for re-conditioning and weighed again to determine the DPM mass. The DPM concentration is then calculated using the sample mass, exhaust gas sample flow rate and sampling duration.

TEST RESULTS

The exhaust emissions data for the 8-mode test cycles are given in Appendix A. Prior to testing, the engine intake restriction at Mode 1 was adjusted to a maximum allowable value of 15.8 inch H_2O for the engine, and similarly exhaust backpressure at Mode 1 was adjusted to a maximum allowable value of 61.5 inch H_2O for all five tests. Data in Appendix A include basic engine parameters, and exhaust emissions. The exhaust backpressure and exhaust temperature at the inlet and the outlet of the devices were also measured.

Table 4 provides 8-mode integrated average values of specific emission data for gases and DPM.

Table 4. Specific exhaust emissions for the integrated 8-mode test cycle

		Baseline Data	Test 1 SC DOC	Test 2 2G CC	Test 3 5G SXC	Test 4 SC DPF
CO_2	g/hr	22106	22326	22103	21962	22177
CO	g/hr	27.7	4.1	4.5	3.8	0.9
NO_2	g/hr	3.6	2.6	7.4	5.6	14.1
NO	g/hr	42.4	44.8	40.5	43.4	37.3
NO_X	g/hr	46.0	47.4	47.9	48.9	51.5
THC	g/hr	8.7	2.2	2.5	2.6	1.2
DPM	g/hr	6.8	6.2	6.0	5.4	0.3

The percent reduction in emissions compared to engine baseline data is calculated using equation 1, and the results for all devices are shown in Tables 5 to 8. A negative value in Tables 5 to 8 indicates an increase.

$$\text{Percent reduction in emission} = \frac{\text{baseline emission} - \text{device emission}}{\text{baseline emission}} \times 100 \qquad \text{Equation (1)}$$

Similarly, incremental decrease in NO_2 emission due to the application of the device is calculated using equation 2. This equation is based on the California Diesel Aftertreatment Verification Procedure program, which limits the incremental increase in NO_2 device emission based on the baseline NO_X emission.

Table 7. Percent mass emission reduction for device 5G SXC

	Baseline Data	Device Value	Device Reduction
CO_2	22106	21962	1
CO	27.7	3.8	86
NO_2	3.6	5.6	-55
NO	42.4	43.4	-2
NO_X	46.0	48.9	7
THC	8.7	2.6	71
DPM	6.8	5.4	20
Incremental % decrease in NO_2 emission			-4

Note: a negative value indicates an increase in emission

Table 8. Percent mass emission reduction for device model SC DPF

	Baseline Data	Device Value	Device Reduction
CO_2	22106	22177	0
CO	27.7	0.9	97
NO_2	3.6	14.1	-292
NO	42.4	37.3	12
NO_X	46.0	51.5	-12
THC	8.7	1.2	87
DPM	6.8	0.3	96
Incremental % decrease in NO_2 emission			-23

Note: a negative value in Table 5 indicates an increase

Project # 603664

Engine Baseline Data

Mode		1	2	3	4	5	6	7	8	Integrated 8-Mode
Speed	rpm	2600	2600	2601	2602	1600	1597	1602	786	2028
Torque	lb.ft	147	111	74	15	189	142	95	2	94
Power	hp	73.0	54.9	36.5	7.4	57.7	43.3	29.0	0.3	38.4
Fuel rate	lb/hr	30.7	22.1	15.6	7.1	21.0	15.2	10.4	1.1	15.8
Exhaust temperature	°F	1123	876	688	417	1010	817	645	234	727
Air inlet restriction	ΔP "H_2O	15.2	13.6	10.7	11.2	6.4	5.5	4.1	1.4	8.8
Exhaust back pressure	ΔP "H_2O	62.2	47.5	36.4	24.5	34.0	24.4	16.6	3.2	32.3
Exhaust flow (wet)	lb/hr	632	594	546	521	428	382	335	179	459
Exhaust gas concentration (wet)										
O_2	%	5.2	8.6	11.4	16.2	4.8	7.8	10.6	18.6	10.5
CO_2	%	9.8	7.6	5.8	2.8	10.0	8.1	6.3	1.2	6.4
CO	%	0.017	0.010	0.013	0.016	0.028	0.008	0.012	0.005	0.013
NO_2	ppm	1	4	17	31	2	10	21	16	12
NO	ppm	202	205	150	76	377	322	193	94	194
THC	ppm	65	79	108	143	44	73	102	90	87
DPM (wet)	mg/m^3	84.3	24.0	22.6	8.4	107.1	27.6	35.3	2.3	37.8
Specific emissions (wet)										
CO_2	g/hr	42533	31143	21984	10129	2941	21246	14492	1524	22106
CO	g/hr	46.0	24.7	31.2	36.6	51.6	12.6	16.9	3.9	27.7
NO_2	g/hr	0.5	1.6	6.7	11.4	0.6	2.6	5.0	2.0	3.6
NO	g/hr	59.9	56.1	38.1	18.3	75.4	57.1	30.0	7.8	42.4
NO_X	g/hr	60.5	57.8	44.8	29.7	76.0	59.7	35.0	9.8	46.0
THC	g/hr	9.0	10.1	12.8	16.2	4.1	6.1	7.4	3.5	8.7
DPM	g/hr	18.6	5.1	4.4	1.6	16.0	3.7	4.2	0.2	6.8

Project # 603664

CEP Catalyst Test#3-5G SXC

Mode		1	2	3	4	5	6	7	8	Integrated 8-Mode
Speed	rpm	2601	2600	2600	2600	1600	1600	1601	785	2028
Torque	lb.ft	149	111	74	15	194	142	95	3	95
Power	hp	73.9	54.9	36.6	7.3	59.0	43.3	28.9	0.5	38.7
Fuel rate	lb/hr	30.2	21.8	15.4	6.8	21.0	15.0	10.3	1.1	15.6
Exhaust temperature	°F	1114	857	674	404	1000	814	642	229	717
Air inlet restriction	ΔP "H_2O	14.9	12.2	10.5	11.2	6.6	5.2	3.9	1.3	8.5
Exhaust back pressure	ΔP "H_2O	60.4	45.7	34.2	23.1	30.1	21.3	15.2	3.1	30.5
Exhaust flow (wet)	lb/hr	637	602	552	526	442	390	337	177	465
Exhaust gas concentration (wet)										
O_2	%	5.4	8.9	11.6	16.5	5.3	8.2	10.8	18.7	10.8
CO_2	%	9.7	7.4	5.7	2.7	9.7	7.8	6.2	1.2	6.3
CO	%	0.0006	0.0004	0.0002	0.0115	0.0004	0.0000	0.0000	0.0049	0.0021
NO_2	ppm	1	15	10	4	36	68	30	9	19
NO	ppm	218	200	164	102	396	275	185	99	198
THC	ppm	9	13	21	101	10	10	15	54	28
DPM (wet)	mg/m^3	71.9	21.0	19.2	6.2	63.8	21.6	30.7	1.1	29.2
Specific emissions (wet)										
CO_2	g/hr	42483	30762	21824	9685	29576	21107	14384	1507	21962
CO	g/hr	1.8	1.1	0.5	26.4	0.8	0.0	0.0	3.8	3.8
NO_2	g/hr	0.3	6.5	3.9	1.4	11.1	18.6	7.0	1.1	5.6
NO	g/hr	63.6	54.8	41.3	24.4	79.9	49.4	28.5	8.0	43.4
NO_X	g/hr	63.9	61.3	45.2	25.7	91.1	68.0	35.5	9.1	48.9
THC	g/hr	1.2	1.6	2.5	11.6	1.0	0.9	1.1	2.1	2.6
DPM	g/hr	16.0	4.5	3.8	1.2	9.9	3.0	3.7	0.1	5.4
Pressure at device inlet	"H_2O	60.4	45.7	34.2	23.1	30.1	21.3	15.2	3.1	30.5
Pressure at device outlet	"H_2O	66.2	49.6	36.6	25.5	32.8	23.1	16.3	3.8	33.2
Temperature at device inlet	°F	1064	822	647	390	938	769	605	223	684
Temperature at device outlet	°F	1013	790	627	379	886	725	579	221	655