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Active Diesel Particulate Filters and Nitrogen Dioxide Emission Limits

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Abstract

Diesel engines are major source of nitrogen oxides (NOx). NOx, primarily nitric oxide (NO) and nitrogen dioxide (NO_2), are formed at high temperatures during diesel fuel combustion. While neither NO nor NO_2 are desirable, NO_2 is the more reactive gas associated with health problems. Both US Environmental Protection Agency (US-EPA) and California Air Resources Board (CARB) initiated rulings for diesel emissions retrofit technologies to limit NO_2 emissions increase "slip" to 20% over the engine baseline emissions. In this paper, an active diesel particulate filter that reduces NO_2 emissions is presented. The active diesel particulate filter utilizes a porous sintered metal filter medium, which is divided into pleated filter strips. These filter strips are regenerated (cleaned) by applying direct electric heating to burn off accumulated soot. Exhaust emissions measurements show that a degreened active diesel particulate filter reduces NO_2 by 42% from the diesel engine exhaust. The data also show that the efficiency of NO_2 emissions reduction improves with aging. Following a break-in or "aging" period, the active diesel particulate filter achieved 96% NO_2 reductions. This far exceeds latest US-EPA and CARB verification standards on NO_2.

Keywords: Diesel emissions**,** Nitrogen dioxide**,** Diesel particulate filter

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1 Introduction

Diesel emissions consist of different exhaust components that include particulate matter (PM), carbon monoxide (CO), total hydrocarbons (THC), and nitrogen oxides (NOx). PM is a complex mixture of extremely small particles (soot) and liquid droplets, primarily incompletely burnt fuel. The small particles adsorb other toxins from the engine and engine exhaust, which can cause adverse health effects including cancer and other pulmonary and cardiovascular diseases. In enclosed spaces, CO resulting from incomplete fuel combustion, is known to cause headaches, dizziness and lethargy, and in extreme cases, death. THC, a contributor to smog, will cause lung irritation in similar environments. NOx, primarily nitric oxide (NO) as well as some nitrogen dioxide (NO_2), are formed at high temperatures during diesel fuel combustion. While neither NO nor NO_2 is desirable, NO_2 is the more reactive gas associated with significant health problems. Scientific evidence links NO_2 exposures, with adverse respiratory effects, [1-3]. Several studies were also done to investigate the health effect of children exposure to diesel exhaust in school buses, [4, 5]. Their conclusions show that diesel emissions have been associated with health problems, being potentially harmful to children near school buses.

1.1 Passive regeneration

Regeneration of Passive Diesel Particulate Filters (PDPF) relies on NO_2 as an oxidizer of carbon to clean the filter and maintain low engine backpressure [6-10]. This technique requires that NO_2 be generated by the oxidation catalyst of the remediation device. During passive regeneration, NO, C, THC, and CO in the exhaust stream are oxidized in the following manner:

$$\mathbf{2NO + O_2 \rightarrow 2NO_2}$$
$$\mathbf{C + NO_2 \rightarrow CO + NO}$$
$$\mathbf{2CO + O_2 \rightarrow 2\,CO_2}$$
$$\mathbf{THC + O_2 \rightarrow x\,CO_2 + y\,H_2O}$$

In most PDPFs, an excess of NO_2 is produced and only partially used in the carbon oxidation process, thus causing NO_2 slip to the atmosphere. NO_2 slip from exhaust remediation devices is highly undesirable and is the main reason why US-EPA and CARB have limited NO_2 increase to 20% of engine baseline for diesel retrofits [11-13]. The National Institute for Occupational Safety and Health (NIOSH) studies have also shown a significant increase in NO_2 concentrations in mine air, resulting from the use of catalyzed filters, [14]. Because NO_2 is a lung irritant, a ceiling value of 5 ppm has been set to lower miners' exposure.

1.2 Active regeneration

Active regeneration of diesel particulate filters is done through different ways and strategies. This paper focuses on an Active Diesel Particulate Filter (ADPF) that consists of active filter cartridges and Diesel Oxidation Catalysts **(**DOC) downstream as shown in Figure 1. An exploded view of an ADPF with four stacks is shown in Figure 2. Each stack has four active filter cartridges. ADPF uses direct electrical heating to burn the accumulated PM and regenerate or "clean" the filter cartridges.

Figure 1: Active Diesel Particulate Filter (ADPF) with Diesel Oxidation Catalysts (DOC) downstream

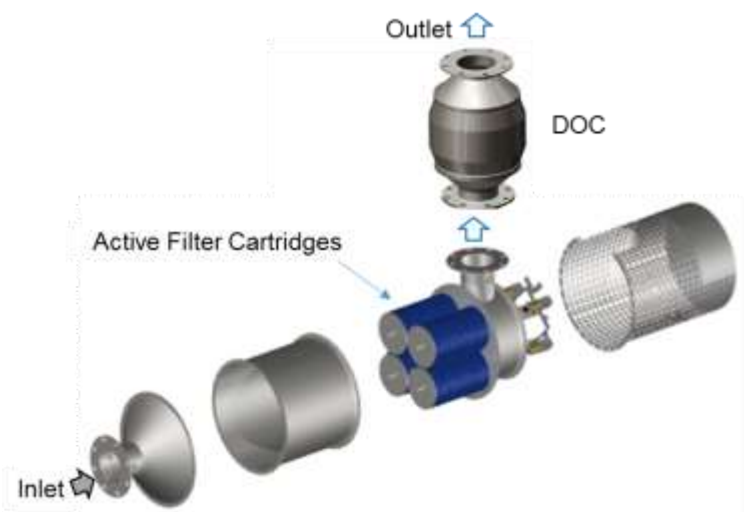

Figure 2: Exploded view of an Active Diesel Particulate Filter (ADPF)

The ADPF utilizes a filter media made of porous sintered metal fibers, shown Figure 3, made of Fecralloy, which contains iron, chromium, aluminum and yttrium. The added aluminum improves resistance to corrosion at high temperature, while yttrium, a rare earth metal, serves to anchor the protective aluminum oxide layer to the surface of the base metal. The filter media consists of multilayers with different fiber size. The graded filter medium is designed for maximum dirt holding capacity and high filter efficiency. The total area of the filter is divided into pleated filter strips, which are packaged as active filter cartridges shown in Figure 4. Dividing the filter area into strips allows for partial regeneration of the total filter area, which reduces the maximum electric power requirements for regeneration. To manage regeneration cycles for the whole filter system, a microprocessor controller is used to monitor and keep the filter cartridges functioning at low backpressure during normal operation.

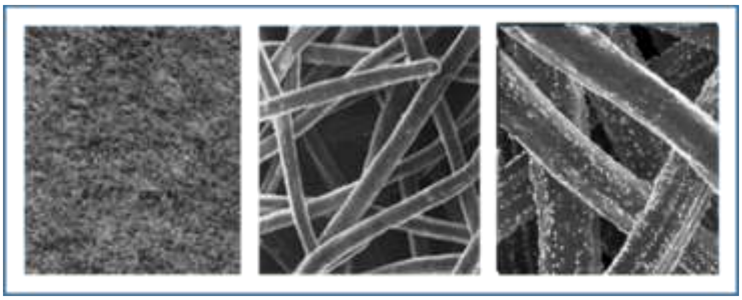

Figure 3: Sintered metal fibers

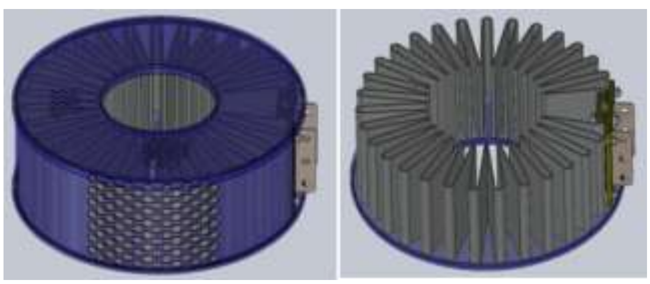

Figure 4: Active filter cartridge, flow from outside to inside

Active regeneration does not rely on NO_2 as an oxidizing agent of carbon (soot), keeping NO_2 at or below engine baseline levels. Specially designed oxidation catalysts, attached to the outlet, reduce CO and THC without converting NO to NO_2. It has been well established that activated carbon is an excellent adsorbent for both gases and liquids and it has been used as reducing agent for NO_2 [15-18]. The soot, similar to activated carbon is able to adsorb hydrocarbons and other gases as the exhaust flows through the soot layer. Soot is collected on the filter medium as a fluffy layer, resulting in high surface area, thereby reducing NO_2

from the diesel engine exhaust stream directly by reacting with carbon, C.

During normal operation or active regeneration, C, THC, and CO in the exhaust stream is oxidized in the following manner:

During normal operation

$$NO_2 + C \rightarrow CO + NO$$

During Active Regeneration Cycle-Thermal Oxidation

$$NO_2 + C \rightarrow CO + NO$$
$$2C + O_2 \rightarrow 2\,CO$$
$$C + O_2 \rightarrow CO_2$$

Using special oxidation catalysts downstream

$$2CO + O_2 \rightarrow 2CO_2$$
$$THC + O_2 \rightarrow x\,CO_2 + y\,H_2O$$

3 Emissions Measurements

The test was performed by Emission Research and Measurement Division (ERMD) of Environment Canada. The emissions were sampled and analyzed using the ERMD Dynamic Dilution On/Off-road Emissions Sampling System. Emission rates were determined for CO, NOx, NO_2, THC and PM. Two active diesel particulate filters (ADPFs) were tested: the first ADPF had been aged in a durability test of 525 hours; the second ADPF had been degreened for 25 hours.

3.1 Test bed

The test bed was a diesel generator set (Genset). The exhaust emission measurements are evaluated by using Genset with a Caterpillar engine model 3306B, 1994. Details of engine specification are provided in Table 1.

Table 1: Engine specification

Engine Model	3306B
Year	1994
Displacement	10.45L
Rated Power	281 kW @ 1800 rpm
Engine Configuration	In Line 6, Turbo, AA cooling

2.2 Test cycle

The Genset emissions measurements were then sample and analyzed using the ERMD Dynamic Dilution On/Off-road Emissions Sampling System. Testing took place over the five modes described in ISO 8178-4 Cycle D2, shown in Table 2. The fuel used was Eastern Region Ultra Low Sulphur Diesel fuel (< 15 ppm sulfur). Each mode represents different test engine application at a rated speed of 1800 rpm.

Table 2: ISO 8178-4 D2 five mode test cycle

Torque	Speed	Weighting Factors
100		0.05
75	Rated Speed	0.25
50	(1800 rpm)	0.30
25		0.30
10		0.10

3 Results and discussion

The measured emissions consist of oxides of nitrogen, nitrogen oxide, carbon monoxide, particulate matter and total hydrocarbons. Each test configuration had a minimum of three valid tests. The average weighted emission rates in grams per kilowatt-hour can be found in Table 3.

Table 3: Summary the average weighted emissions in g/kWh

Test Configuration	CO	NOx	NO_2	THC	PM
OEM (baseline)	1.92	9.1	0.47	0.95	0.168
After Treatment: Degreened ADPF	0.31	8.4	0.27	0.23	0.022
After Treatment: Aged ADPF	0.11	8.5	0.02	0.22	0.011

As shown in Figure 5, PM was reduced by 87% for the degreened unit, and 93% for the aged unit. Both units show reductions of 84 and 94% in CO, and reductions greater than 75% in THC. The results show a significant reduction in NO_2 for aged system, over 90% compared to 42% for the degreened units.

In Figure 6, the NO_2 emissions of the Original Engine Manufacturer (OEM) baseline, the degreened and aged units are plotted as function of exhaust temperature. The results show that the aged unit has a significant reduction in NO_2 in the entire temperature range. The degreened unit, however, shows much less reduction in NO_2 emissions especially at high temperature. The uncertainty in NO_2 measurements were low for the aged unit compared to the OEM baseline and the degreened unit. Both the degreened and aged units show small reductions in NOx, about 7%. Plotted in Figure 7, is NOx emissions as a function of temperature for the OEM baseline, the degreened unit, and the aged unit. It clear from the plots, there is a slight reduction in NOx emissions and that both the degreened and aged units have the same NOx emissions output.

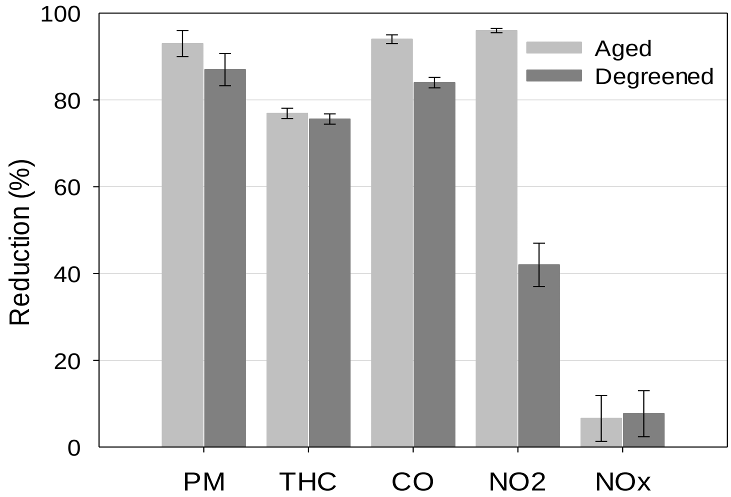

Figure 5: Emission reductions

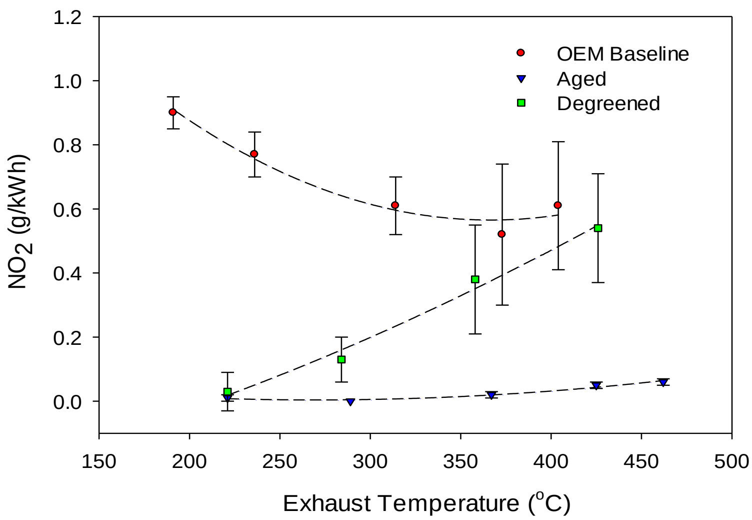

Figure 6: Nitrogen dioxide emissions vs. exhaust temperature

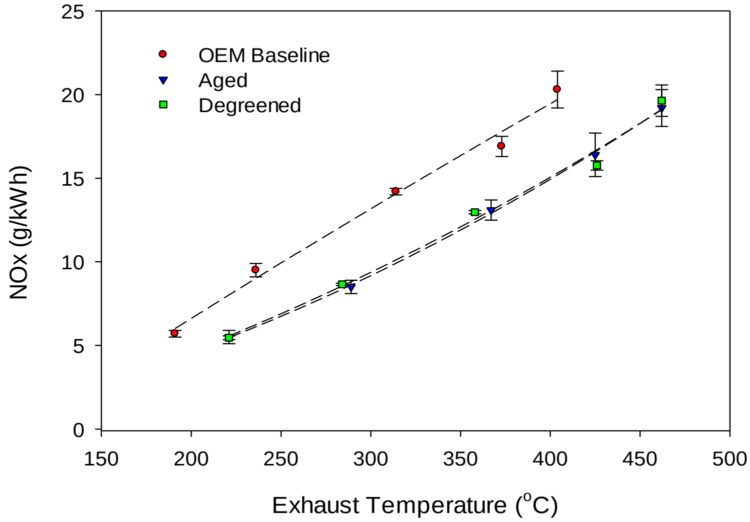

Figure 7: Nitrogen oxides emissions vs. exhaust temperature

4 Conclusions

Regeneration of passive diesel particulate filters mostly relies on NO_2 as an oxidizer to regenerate (clean) the filter. This technique requires that NO be oxidized into NO_2 by platinum based diesel catalysts. In most passive diesel particulate filters, an excess of NO_2 is produced, and only partially used in the carbon oxidation process, thus causing NO_2 slip into the atmosphere. NO_2 is considered potentially one of the most harmful emission gases in diesel exhaust. On a world-wide basis, recommendations are being made to limit the conditions under which NO_2 are produced. These include diesel engine management and exhaust after-treatment. US-EPA and CARB have proposed and initiated rulings to limit NO_2, especially for emission control systems that increase these levels >20% over engine baseline levels. Active regeneration, using direct electrical heating, does not rely on NO_2 as an oxidizing agent of carbon. It has demonstrated a novel process to significantly reduce NO_2. NO_2 reduction was accomplished by using soot as a reducing agent. Special oxidation catalysts, which are designed to minimize the oxidation of NO into NO_2, were used downstream of the filter systems. The result is over 90% reduction in NO_2 for an "aged" system.

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