

Effect of Coolant Exposure on Diesel Exhaust Aftertreatment Performance

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ABSTRACT

Aftertreatment devices are exposed to exhaust poisons from fuel, oil and coolant. Studies on fuel and lubricant based poisoning have been widely published. However, diesel oxidation catalyst (DOC) and catalyzed soot filter (CSF) performance after exposure to constituents of coolant is not fully understood. Exhaust gas recirculation (EGR) cooler failure can cause a coolant leak into the exhaust that can reach the exhaust aftertreatment system. Coolant contains elements that can cause deterioration of aftertreatment components. This study focuses on the poisoning effect of coolant on the performance of a DOC + CSF system. The coolant introduction simulates an engine failure such as an EGR cooler internal fracture. DOC NO oxidation, quenching and hydrocarbon (HC) slip control performance during active regenerations are evaluated after slow and after consecutive fast coolant introduction and compared to the performance before the coolant exposure. Total aftertreatment coolant exposure was equal to 1.9x and 3.8x of DOC volume for the slow and the fast coolant introduction, respectively. The DOC NO oxidation performance is negatively affected by both the slow and fast coolant injection. A decrease in NO₂ production is observed on both degreened and high temperature aged DOC. The DOC quenching and HC slip control experiments also confirm that the DOC performance is affected by the coolant exposure. The performance of the CSFs is also studied. Post mortem characterization of the after-treatment components that probes the distribution of the coolant elements and the catalytic deactivation as a function of the catalyst length is carried out.

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INTRODUCTION

A majority of heavy duty diesel (HDD) equipment uses DOC-CSF exhaust aftertreatment systems in order to meet particulate matter (PM) standards established in USA and Europe for on-road and off road machinery [1-2]. The DOC component in DOC-CSF systems serves several purposes, all based on the oxidation of a gaseous species in the exhaust. First, it oxidizes diesel fuel injected into the exhaust stream to generate heat for combusting soot trapped in the CSF. Second, the DOC converts NO to NO₂ which enables soot removal at lower temperature through "passive filter regeneration". Third, it oxidizes the engine out HC, CO and soluble organic fraction (SOF) during normal engine operations. The CSF component has two primary functions. First, it provides PM trapping function. Second, the CSF washcoat eliminates HC that passes through the DOC un-

reacted during filter regeneration and CO that is generated during soot combustion. The CSF washcoat also generates additional NO₂ to support passive filter regeneration.

It is well-established in the automotive industry that exhaust aftertreatment system performance deteriorates over its lifetime due to thermal deactivation (mostly PGM and to a lesser extent washcoat sintering) and due to poisoning (chemical poisoning and physical masking/fouling) [3]. Thermal deactivation can be reduced with development of calibration strategies that decrease the regeneration temperature and frequency and through introduction of new, thermally durable DOC and CSF washcoat formulations. Thus, the contribution of poisoning to the overall DOC-CSF performance degradation is expected to increase as aftertreatment system control and catalyst formulations mature.

In HDD applications, aftertreatment devices are exposed to exhaust poisons from fuel, oil and coolant. Studies on fuel and lubricant based poisoning have been widely published [3, 4, 5, 6, 7]. However, DOC and CSF performance after exposure to constituents of coolant is not fully understood. In contrast to fuel and oil-derived poisoning, coolant poisons exposure occurs only in case of engine failures such EGR cooler and head gasket leaks. EGR cooler failure can cause coolant leaks into the exhaust that can reach the exhaust aftertreatment system by going through the engine combustion system. Coolants for HDD applications are formulated to prevent corrosion and cylinder liner cavitation for extended period of time. Fully formulated HDD coolants may contain significant quantities of S (sulfur), P (phosphorus), Si (silicon), Na (sodium) and K (potassium), known to affect aftertreatment components performance [7].

This paper describes the effect of coolant exposure on DOC and CSF performance characteristics. NO oxidation, HC quenching behavior and HC slip control characteristics of the DOC are evaluated after slow and after consecutive fast coolant introduction and compared to the performance before the coolant exposure. Similarly, the HC, CO and NO oxidation performance of the CSFs is also studied before and after coolant poisoning. Post mortem characterization of the after-treatment components includes X-ray fluorescence (XRF) analysis, Scanning Electron Microscopy (SEM) imaging and core reactor testing to understand the distribution of the coolant elements and the catalytic deactivation as a function of the catalyst length.

EXPERIMENTAL

CATALYST SAMPLES

All DOC and CSF samples were coated with commercial washcoat technologies. The DOC substrates were round, 9.5 inches in diameter with a honeycomb structure featuring 400 cells per square inch and 7 mil wall thickness. The DPF substrates were also 9.5 inches in diameter with a honeycomb structure featuring 200 cells per square inch and 12 mil wall thicknesses. The length of the DOCs was 6 inches (degreened DOC) and 5 inches (aged DOC); the length of the CSFs was 9 inches. The catalysts samples were canned using prototype canning process prior to aging. [Table 1](#) provides details of the samples including the aging conditions.

The DOC and CSF samples were coated with Pt-Pd based catalyst technologies. DOC and CSF samples were evaluated in degreened and aged conditions. The degreening and aging of the samples were carried out in an accelerated manner on an engine running in a test cell. The first DOC + CSF system was degreened for a total of five hours targeting DOC and CSF bed temperatures of 500 °C. The second system was aged for a total of 800 cycles using a protocol that included operation of the engine at 2200 rpm and 955 lb-ft (1300 kg/h wet exhaust flow and 400 °C DOC inlet temperature), and a closed-loop temperature control of an in-exhaust fuel doser to achieve DOC outlet temperature of 650 °C. One aging cycle

consisted of 15 minutes of dosing followed by 15 minutes of normal mode operation (i.e., no fuel dosing). Typical bed DOC and CSF bed temperatures during were 650 - 660°C and 675 - 685 °C, respectively.

Table 1. Samples description and aging conditions

Sample ID	PGM	Dimensions		Aging conditions
		Diameter in (mm)	Length in (mm)	
DOC-A	Pt-Pd	9.5 (241.3)	6.0 (152.4)	Degreened 500 °C/5 h
CSF-A	Pt-Pd	9.5 (241.3)	9.0 (228.6)	Degreened 500 °C/5 h
DOC-B	Pt-Pd	9.5 (241.3)	5.0 (127.0)	Aged 800 cycles
CSF-B	Pt-Pd	9.5 (241.3)	9.0 (228.6)	Aged 800 cycles

TEST CELLS AND TEST ENGINE

Two John Deere engines (a 6.8L and a 9.0L, 6-cylinder PowerTech Plus) were used in this study. These Tier 3 engines utilize cooled exhaust gas recirculation, a variable geometry turbocharger and a high-pressure common rail fuel injection system.

Two different engine test cells were utilized for this investigation. A test cell equipped with an Eddy current dynamometer rated to 1000 hp (746 kW) was utilized for the accelerated ageing of the catalyst samples along with the Tier 3 John Deere 9.0L 6-cylinder PowerTech Plus engine. For the performance testing a cell equipped with an Eddy current dynamometer rated to 500 hp (373 kW) was utilized with the Tier 3 John Deere 6.8L 6-cylinder PowerTech Plus engine. The emissions were measured using a Horiba MEXA 7100D Series bench and a MKS 2030-HS Series FTIR as a secondary source to verify data collection quality. In addition, a heated flame ionization detector (HFID) was utilized to measure hydrocarbons (HC).

Axial configuration for inlet and outlet cones was utilized in both test cells. Both cells were equipped with a commercial airless in-exhaust hydrocarbon injection (HCI) system. The injection module was installed at a 45° angle on a section of straight pipe downstream of the turbocharger. Approximately, six feet of exhaust pipe with one 90 degree bend were extended between the fuel injector and the DOC inlet. The DOC + CSF and entire exhaust pipe were insulated using ceramic fiber blanket to reduce heat loss and minimize test to test variation.

COOLANT POISONING EXPERIMENTS

A modern commercial coolant designed for heavy-duty engine use was utilized in the experiment. In a single poisoning experiment 6.5L of coolant was injected in the exhaust pipe right after the turbocharger by an injector placed perpendicular to the straight exhaust pipeline. This amount represents worst case exposure before internal coolant leak is repaired. The coolant was injected through a multi-hole $\frac{1}{4}$ " probe assisted by a pump and a solenoid valve controlled by frequency modulation. The DOC was four feet from the coolant injection point. Figure 1 shows a schematic of the exhaust configuration along with the coolant injection setup.

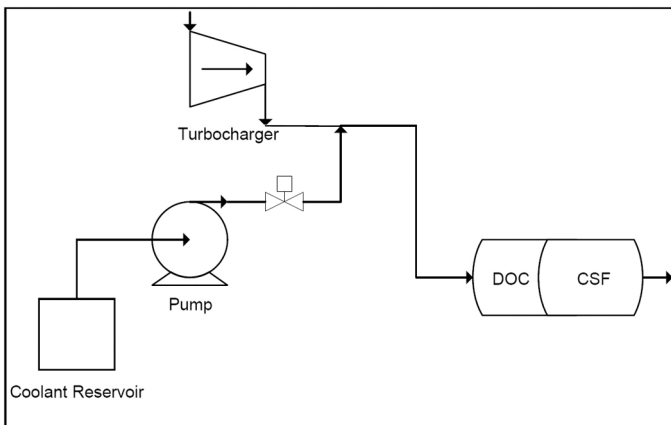


Figure 1. Test cell setup for coolant dosing

The 6.8L engine was run at 1500 rpm and 766 lb-ft torque during the coolant injection yielding a DOC inlet temperature of $\sim 470^\circ\text{C}$ and 787 kg/h wet exhaust flow. The first coolant injection event used 6.5L coolant during a 12 hour period and represents the “slow poisoning” condition. After the first coolant injection was completed, regeneration of the system was carried out in the same configuration by injecting fuel to achieve DOC outlet temperature around 620°C for 15 minutes. Then a second “slow poisoning” event was carried out at the same speed and load by injecting an additional 6.5L of coolant over 12 hours, followed by a second regeneration event. After these two “slow” coolant injection cycles, the catalysts were tested for NO oxidation performance and HC slip control (described in the next section).

Once the performance testing was completed the first “fast” coolant injection event was carried out by introduction of 6.5L of coolant in a 2.5 hour period, followed by a regeneration of the system. The fast coolant injection and regeneration were repeated one more time to achieve a total of 13L of coolant injected in a five hour period. Performance testing was carried out after the second regeneration to determine the effect of “fast” coolant injection rate in the DOC and CSF.

PERFORMANCE TEST CONDITIONS

The DOC and CSF samples were tested on engine with two different 6-point steady state cycles (Figures 2 and 4). Each DOC or CSF sample was installed and tested individually to determine its steady state NO oxidation performance at different catalyst inlet temperatures and wet exhaust flow rates. The temperature for the DOC steady state points varied from 150 to 450°C and the exhaust flow rate from 750 to 1300 kg/h, corresponding to a GHSV of 90,000 - 186,000 h^{-1} for DOC. CSF samples were tested in the $240 - 445^\circ\text{C}$ temperature range with an exhaust flow rate of 800 to 1000 kg/h corresponding to a GHSV of 64,000 - 75,000 h^{-1} .

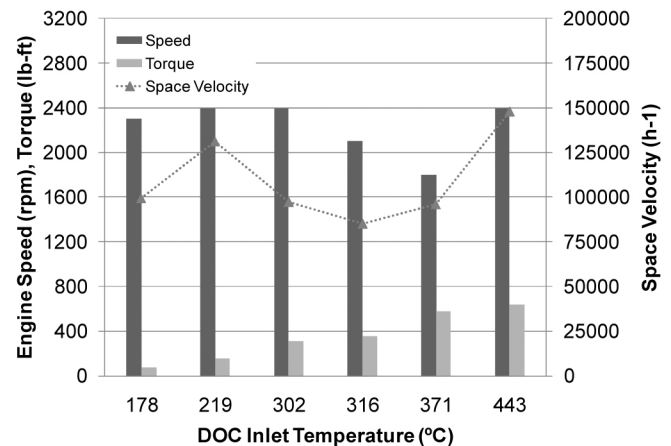


Figure 2. Engine and exhaust conditions during the DOC NO oxidation test

The DOC quench test was carried out as described by Kozlov et.al. [2]. The engine was stabilized at 1700 rpm and 572 lb-ft to achieve 380°C at DOC inlet. Diesel fuel was slowly injected to achieve DOC outlet temperature of $610 \pm 5^\circ\text{C}$ and this temperature was maintained for 10 minutes using closed loop control. The torque was then reduced at constant rate while maintaining DOC-out T at $610 \pm 5^\circ\text{C}$. This resulted in a decrease of the DOC inlet temperature and wet exhaust flow from 780 to 455 kg/h, which corresponded to a GHSV of 112,000 h^{-1} to 65,000 h^{-1} . The HC slip and DOC inlet temperature were recorded to determine the point where the DOC quenches and an increase of DOC out HC concentration is observed. Details of the specific engine and test conditions for both NO oxidation and HC slip are shown in figures 2, 3, 4.