

Engine Test for DOC Quenching in DOC-DPF System for Non-Road Applications

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John Deere Power Systems

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ABSTRACT

The use of a diesel oxidation catalyst (DOC) in conjunction with a diesel particulate filter (DPF) is now a well-established aftertreatment system design for on-road heavy duty diesel. For non-road applications, the DOC must respond to the need for performance under more diverse and less favorable conditions, such as operation at low loads in cold weather. To choose a DOC technology for such applications, one must have practical and meaningful tests that address the specific catalytic functions of interest such as hydrocarbon oxidation to produce heat for regenerating DPF. This paper describes the development of an engine test protocol that focuses on resistance to the phenomenon known as quenching, the cessation of hydrocarbon (HC) oxidation that occurs when the exhaust temperature decreases below the light-off temperature of the catalyst. During development, the sensitivity and repeatability of the test were carefully scrutinized. As a result, the test clearly discriminates between catalysts with different platinum group metal (PGM) definitions (loading and ratio), as well as between different aging durations and types (on-engine vs. hydrothermal oven aging).

INTRODUCTION

The application of the DPF to heavy duty diesel (HDD) exhaust aftertreatment is now well-established for on-road applications. Not surprisingly, many non-road equipment manufacturers will adopt this same technology in order to meet Interim Tier 4 and Stage 3b regulations for 2011 and beyond [1].

A majority of HDD DPF systems include a DOC. This aftertreatment component may serve several purposes, all based on the oxidation of a gaseous species in the exhaust. In a DPF system, its most important function is likely to be

“enable active regeneration”. During active regeneration, the DOC produces heat to ignite and combust completely the soot trapped in the DPF, while ensuring that temperatures within the DPF do not exceed design limits. This heat results from the oxidation of a significant quantity of hydrocarbons (HC), coming from the injection of fuel into the exhaust stream, or an additional late injection in the cylinders.

Generation of heat by the DOC requires that the catalyst be active. The catalyst will not be active under cold conditions, but with increasing temperature it will exhibit a relatively sharp increase in the rate of HC oxidation, a phenomenon referred to as “light-off” [2, 3]. For the sake of this discussion, let's assume the light-off temperature is 280°C.

Given the extreme environmental conditions encountered by many non-road applications, an exhaust temperature exceeding the light-off temperature of the DOC is far from guaranteed. Consequently, it is necessary to provide the engine with capability to increase the exhaust temperature. The control strategy would include an exhaust temperature threshold that would have to be attained before HC would be provided to the DOC. Let's assume that this threshold is 300°C. Note that, with this choice, there is engineering safety margin between the light-off temperature of the catalyst and the threshold to initiate regeneration.

Once regeneration has commenced, it is possible (for non-road applications one might even say probable) that the exhaust temperature will decrease below 300°C. It is highly desirable to complete the regeneration once it has been started, so one might choose to allow the exhaust temperature to go below the threshold value noted above before terminating fuel injection. As the temperature continues to decrease, the catalyst exhibits a phenomenon known as “quenching” or “extinction” [4], characterized by a sharp increase in the HC concentration in the exhaust downstream

of the DOC. This results from a sharp drop in the conversion efficiency of the catalyst. The mechanism of quenching may be described as a smothering of the catalyst's active sites by HC and incomplete oxidation products, (e.g. CO); oxygen is prevented from reaching the active sites, so oxidation of the HC ceases.

There are significant negative consequences when quenching occurs during active regeneration. If the DPF is not catalyzed, the HC that passes through the DOC un-reacted will also slip through the DPF, resulting in an unacceptably high emission to the environment. Using catalyzed DPF mitigates HC slip, but the additional HC oxidation will result in heat that is not accounted for with respect to thermal management of the DPF. Thus, there is a higher risk of thermal shock to the DPF, which must be avoided in order for that component to maintain its function.

It can be argued that characterizing the light-off behavior of a DOC is sufficient to understand its quenching behavior. However, as will be detailed below, there are unique aspects to the quenching phenomenon. In addition, the results from a quenching test can be used to define directly the control temperature at which fuel injection should be terminated.

This paper describes a test protocol that was developed to characterize quenching, both for catalyst technology selection and for controls calibration. In the course of this work, the use of multiple thermocouples located within the DOC helped to identify a new detection method for quenching. Particular attention was paid to the repeatability of the test; as a result, a means of compensating for sources of long-term variation in the test cell was utilized.

EXPERIMENTAL

CATALYST SAMPLES

All DOC samples were acquired from the same catalyst supplier and were coated with a commercial washcoat technology. The substrates were round, 12 inches in diameter and 5 inches long (305 mm $\times$ 127 mm), with a honeycomb structure featuring 400 cells per square inch (62 cells/cm²) and 7 mil (0.18 mm) wall thickness and wall thickness). [Table 1](#) provides details of the samples including the hydrothermal aging conditions. This aging was carried out with a flow of 10% water in air and used a Thermcraft oven equipped with a stainless steel retort insert. DOC bed temperatures were monitored throughout each aging to ensure consistency and quality of oven aging. The hydrothermally aged DOCs were then canned using a commercial canning design and process.

Table 1. Description of oven aged DOC samples

DOC ID	PGM loading	Pt/Pd ratio	Aging conditions
OA-1	Low	Medium	700°C/ 200 h
OA-2	Medium	Low	700°C/ 200 h
OA-3	Medium	Low	700°C/ 400 h
OA-4	Medium	Medium	700°C/ 100 h
OA-5	Medium	Medium	700°C/ 200 h
OA-6	Medium	Medium	700°C/ 300 h
OA-7	Medium	Medium	700°C/ 400 h
OA-8	Medium	High	700°C/ 200 h
OA-9	Medium	High	700°C/ 400 h
OA-10	High	Medium	700°C/ 200 h
OA-11	High	Medium	700°C/ 400 h

One 12" $\times$ 5" sample with the medium level of precious metal loading and the medium Pt:Pd ratio was aged in an accelerated manner in an engine dynamometer test cell as part of DOC-cDPF system. In this case DOC was canned prior to the aging. The aging was conducted "progressively", in a series of four equal stages, with performance testing conducted at the end of each stage. The aging protocol included operation of the engine at 2200 rpm and 1295 Nm (1670 kg/h wet exhaust flow and 400°C DOC inlet temperature), and closed-loop control of an in-exhaust fuel doser to achieve a DOC-outlet temperature of 650°C. One cycle of the aging test consisted of 15 minutes of dosing, followed by 15 minutes of normal mode operation (no dosing). Each stage of the aging included 400 cycles; after the fourth stage the sample had experienced a total of 1600 cycles. In the results presented below, this sample is given a unique name after each stage of aging as shown in [Table 2](#) (DOC IDs EA-1 through EA-4).

Table 2. Description of engine aged DOC samples

DOC ID	PGM loading	Pt/Pd ratio	Aging conditions
EA-1	Medium	Medium	400 cycles
EA-2	Medium	Medium	800 cycles
EA-3	Medium	Medium	1200 cycles
EA-4	Medium	Medium	1600 cycles
EA-5	Medium-high	Medium	1600 cycles

One additional DOC sample, EA-5, was used in some follow-up testing. The same washcoat technology at medium-high PGM loading and medium Pt:Pd ratio was applied to a 400/7 substrate that was 10.5 inches in diameter and 6.5 inches long (267 $\times$ 165 mm). The sample was also aged to 1600 cycles as described above.

Prior to engine testing (aging or performance), each DOC was instrumented with fifteen K-type thermocouples (TCs),

always with the same locations (Figure 1). TCs were inserted from the DOC outlet face. The locations were chosen to allow temperature differences in the axial, radial and angular dimensions to be comprehended. The signals from these TCs were recorded continuously in all the experiments, including the engine aging.

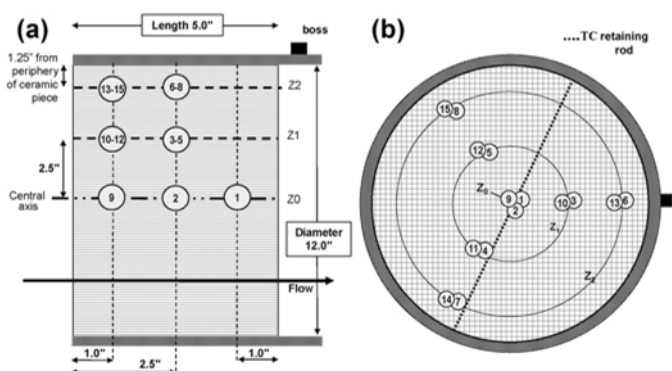


Figure 1. DOC thermocouple map, axial view (a) and view from outlet face (b).

TEST CELLS AND TEST ENGINE

A John Deere 9.0L, 6-cylinder PowerTech Plus engine was used in this study. This Tier 3 engine utilizes cooled exhaust gas recirculation, a variable geometry turbocharger, 4-valve cylinder head, and a high-pressure common rail fuel injection system.

Two different engine test cells were utilized. For the accelerated aging of EA samples, a cell equipped with an Eddy current dynamometer rated to 1000 hp (746 kW) but no emission measurement capability was utilized. For performance testing including development of the DOC quench test, the test cell was again equipped with an Eddy current dynamometer rated to 1000 hp (746 kW) and featured a dual exhaust configuration that allowed for the DOC to be by-passed during engine start up, shut down and troubleshooting. The performance cell also included a Horiba 200 Series test bench. For the measurement of HC, a heated flame ionization detector (HFID) was employed.

The DOC quench test can result in a very high concentration of hydrocarbons entering the emissions sampling system. In this study, fuel dosing was terminated when the HC slip reached 2800 ppm. Nevertheless, this level of HC in the exhaust can still lead to a “memory” in the measurement system. To minimize this effect, the single HC sampling port downstream of the DOC featured a sample line that was only 3 meters long and that was maintained at a constant elevated temperature of 191°C. In addition, the test protocol (described below) was designed to allow for HC to clear the sampling system before the next test was initiated.

All the tests including DOC aging utilized an axial configuration for both the inlet and outlet cones. The exhaust system in both test cells was equipped with a commercial airless in-exhaust hydrocarbon injection (HCI) system. The ECU of the engine was modified to enable control of this system, including closed-loop control to the temperature of the exhaust exiting the DOC. The injection module was installed at a 45 degree angle on a section of straight pipe just downstream of the turbocharger. The total length of exhaust pipe between this injector and the DOC inlet face was over 3 meters, with two 90 degree bends. The entire length of this exhaust pipe was insulated with a ceramic fiber blanket to reduce heat loss (5-20°C) and minimize test-to-test variation, which would otherwise have been magnified by the fact that the test cell temperature was not well controlled, and testing occurred periodically from early winter through late spring.

The exhaust system was also equipped with two commercial temperature sensors positioned 25 and 15 mm from the DOC inlet and outlet face, respectively. These temperature sensors were thermistor type and penetrated about 50 mm into the exhaust flow.

PERFORMANCE TEST CONDITIONS

In a typical test the engine was warmed up to full speed and load conditions (2200 rpm/1295 Nm) while the exhaust was directed through the by-pass loop. After the engine stabilized, the two switching valves of the by-pass loop were used to re-direct the exhaust flow through the DOC, for 10 minutes without fuel injection. Next, HC dosing was initiated and the injection rate was increased slowly until the DOC-out target temperature of 625°C was reached. This temperature was then maintained through closed-loop control. After 10 minutes in this mode, the speed was decreased to 2000 rpm and then the torque was reduced at a constant rate of 35 Nm/min, while maintaining DOC-out temperature of 625°C. This resulted in a gradual decrease in the exhaust temperature measured at the DOC inlet face. The wet exhaust flow decreased from 1570 kg/h to 720 kg/h, corresponding to a gas hourly space velocity (GHSV) of 141,400 h⁻¹ and 64,900 h⁻¹ (NTP), respectively. A plot of these parameters from a representative DOC quench test is presented in Figure 2.