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Development of SCR on Diesel Particulate Filter System for Heavy Duty Applications

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ABSTRACT

Selective Catalytic Reduction (SCR) catalysts have been demonstrated as an effective solution for controlling NOx emissions from diesel engines. Typical 2010 Heavy Duty systems include a DOC along with a catalyzed soot filter (CSF) in addition to the SCR sub-assembly. There is a strong desire to further increase the NOx conversion capability of such systems, to enable additional fuel economy savings by allowing engines to be calibrated to higher engine-out NOx levels. One potential approach is to replace the CSF with a diesel particulate filter coated with SCR catalysts (SCR-DPF) while keeping the flow-through SCR elements downstream, which essentially increases the SCR volume in the after-treatment assembly without affecting the overall packaging. In this work, a system consisting of SCR-DPF was evaluated in comparison to the DOC + CSF components from a commercial 2010 DOC + CSF + SCR system on an engine with the engine EGR on (standard engine out NOx) and off (high engine out NOx). The SCR-DPF system exhibited significantly higher NOx reduction efficiency than the CSF systems under both steady state and heavy duty FTP transient conditions when the engine operated at the same condition. The soot oxidation activity on these two systems was also evaluated. Net soot oxidation (ie more soot removed from the filter than entered it form the engine) was observed over the SCR-DPF system at 400°C presumably because of the high NOx/PM ratio when the engine EGR was turned off. No net soot burn was observed for the 2010 CSF system when operating with standard EGR at the specific conditions chosen for these series of testing. The high passive filter regeneration activity of the SCR-DPF system with the engine operating at high engine-out NOx may result in less frequent active regeneration events and, hence, reduce the fuel penalty associated with active regeneration. The results of this work demonstrated that using SCR-DPF systems not only could meet current NOx reduction regulations but also improve fuel economy for heavy duty diesel vehicles by allowing them to operate at higher engine out NOx conditions.

INTRODUCTION

To meet NOx emission requirements and regulations for heavy duty diesel engines, selective catalytic reduction (SCR) catalysts have been demonstrated to be an effective solution. Urea based SCRs for 2010 heavy duty applications consist of DOC along with a catalyzed soot filter (CSF) in addition to the SCR sub-assembly. Further decrease in NOx emission from an after-treatment system is desired to have additional fuel economy saving by allowing diesel engines operation at higher engine out NOx level. One approach is to replace the CSF with a diesel particulate filter coated with SCR (SCR-DPF) while keeping the flow-through SCR downstream. This approach helps in increasing the SCR volume, which can improve system NOx conversion, without changing the overall package size in a typical 2010 type system. Utilizing the SCR-DPF system could allow the diesel engine to operate at higher engine out NOx while still having the same emission targets and potentially improve the engine fuel economy. For the SCR-DPF system, high porosity filters are needed to enable the use of the high washcoat loadings necessary to get good performance and durability. These high porous filters need to have very good thermomechanical properties to enable them to survive the active regeneration events over the life of the system. Previous work has demonstrated that SCR-DPF catalysts have high NOx conversion capabilities [1, 4]. Also, many investigations have been conducted to understand the thermal durability of Cu-zeolite SCR catalysts and their activity after repeated soot regeneration [1, 2, 3, 4], which allows its use in the SCR-DPF system. It was also demonstrated that SCR-DPF has a similar characteristics as the CSF in that it has a low impact on back pressure [4]. However, limited work has been done to evaluate SCR-DPF for passive regeneration capability in heavy duty applications.

In this work, a system containing an SCR-DPF was evaluated in comparison to a 2010 type CSF + SCR system on an engine with the engine EGR on (auto EGR) and off (high engine out NOx). The NOx conversion of these two systems during steady state and transient (HD FTP cycles) testing was studied to evaluate NOx conversion of the SCR-DPF as compared to the CSF system for heavy duty applications. In order to have the desired fuel economy, the SCR-DPF system must not only have high NOx conversion but also be able to passively regenerate via reaction with NO2. Therefore, passive soot oxidation activity of these two systems was evaluated.

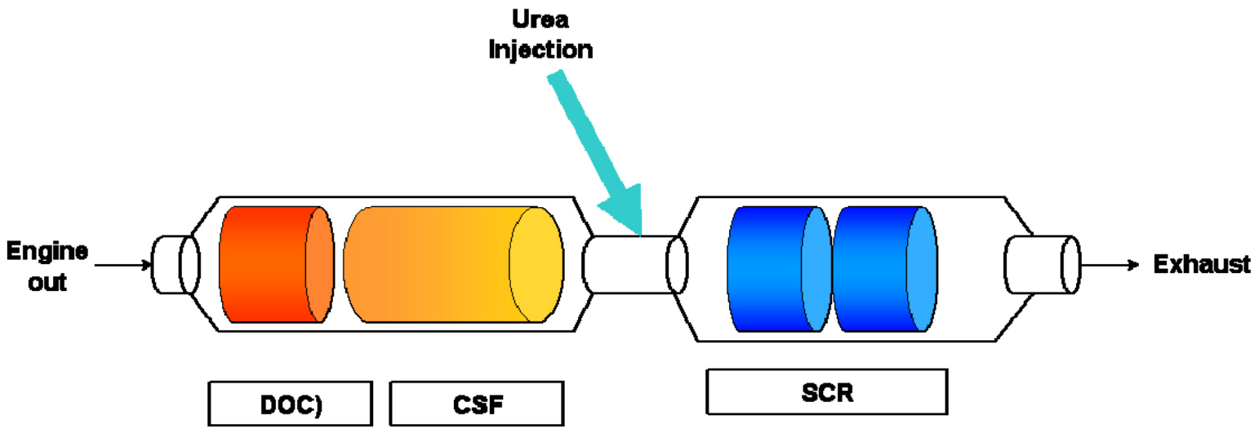
EXPERIMENTAL

Cu-zeolite SCR was washcoated on a high porosity filter. The filter used for this study was a NGK cordierite C650, 300 cells per square inches and 12 mil wall thickness. This catalyst was compared to a current catalyzed soot filter (CSF) which was also coated on NGK cordierite filter substrate with 200 cells/ in^2 and 12 mil wall thickness. Both CSF and SCR-DPF were combined with diesel oxidation catalyst (DOC) upstream and Cu-SCR catalysts downstream. DOC, CSF and SCR-DPF were hydrothermally aged at 700°C for 150hrs while SCR catalysts were aged for 100hrs at 650°C. There was 10% water present during all hydrothermal aging. Table 1 shows catalyst dimensions and aging conditions.

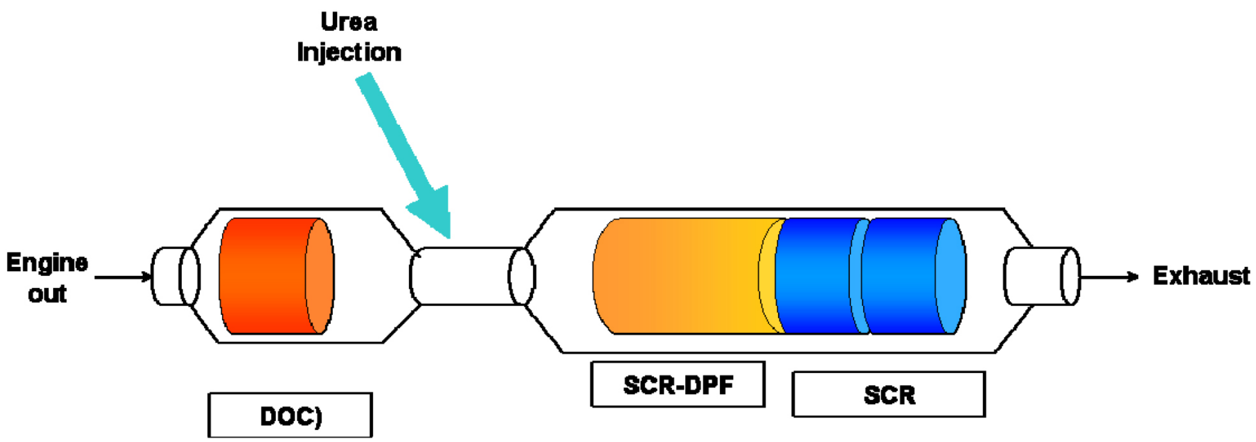
Testing was conducted using a 2007 MY heavy duty diesel engine with a 2007 calibration. The system configuration during all tests was DOC + SCR-DPF (or CSF) + SCRs, the configurations are shown in schematic diagrams 1 and 2. Urea was delivered and injected into exhaust by an air assisted Grundfos pump. The urea injection nozzle was located after the DOC for SCR-DPF system and after the CSF for the DOC + CSF + SCR system. A six inch static mixer was placed after the injection nozzle and before SCR-DPF or SCR bricks to ensure good mixing and uniform distribution in the exhaust.

Table 1. Catalysts Information

	Substrate	Size (in.)	Total PGM (g/ft^3)	Aging Condition
DOC	NGK- 400cpsi/7mil	10.5x4	40	700C, 150hrs, 10% water
CSF	NGK-10.5x12, 200cpsi/12mil	10.5x12	6	700C, 150hrs, 10% water
SCR-DPF	NGK-C650, 10.5x12, 300cpsi, 12mil	10.5x12	NA	700C, 150hrs, 10% water
SCR	NGK - 400cpsi/4mil	(10.5x6)*2	NA	650C, 100hrs, 10% water



Schematic Diagram 1. CSF System configuration



Schematic Diagram 2. SCR-DPF System configuration

Both steady state and transient testing were conducted to determine the performance of the two systems. The SCR-DPF system was tested with EGR off while the CSF system was tested both with EGR off and on. Steady-state tests were conducted at six different speeds and loads, A75, A25, B75, B25, C75 and C25. The ANR (ammonia to NOx ratio) was kept constant at 1.2 during steady state runs. The space velocity during steady-state testing varied between 20K hr^{-1}-55K hr^{-1} depending on the system and test condition. The two system performances were also determined during cold and hot HD FTP cycles. During transient cycles, urea over-dosing strategy at lower temperatures (200-220°C) was used to saturate the SCR and SCR-DPF components. The average ANR during transient cycles was 1.2 for both the CSF system (EGR on) and for the SCR-DPF system (EGR-off).

For passive regeneration testing, the CSF or the SCR-DPF systems were loaded up to 3g soot/l. The passive regeneration capability of each system was studied at DOC inlet temperatures of 300°C and 400°C at speed B. Filters were weighed before and after soot loading and passive regeneration while still hot at around 180°C. The CSF system was passively regenerated with auto EGR (ie low NOx) while SCR-DPF was regenerated with EGR turned off (ie high NOx).

The dynamometer utilized in this study was 800HP AC motoring dyno from Horiba. During transient testing, full dilution tunnel CVS (Horiba 4000 SCFM) was used, and intake air flow was measured with Sierra air flow meter ranging from 0-2400kg/hr with +_1% accuracy in full scale. Engine out emissions were measured using Horiba MEXA 7500D dual bench (CO, HC and NOx) analyzers with +_1% accuracy across the full scale. System out emissions were also measured using an FTIR (MKS model 2030 HS). DPF backpressure was monitored using pressure transducers, Setra Model 206. Soot loadings/regenerations for the filters were measured by weighing the filters while still hot at 180°C. The scale used for weighing the filters was Mettler Toledo, ranging from 0-64Kg with 0.1g resolution. Temperatures in the system were measured using K type thermocouples.

RESULTS

NOx Performance During Steady State

The NOx conversion over Cu-SCR for both SCR-DPF and CSF systems were measured during 6 mode steady state tests with ANR of 1.2. Before the start of steady state testing, the DPFs were actively regenerated at CSF/SCR-DPF inlet temperature of 600°C to remove soot. SCR-DPF performance was determined by turning off the EGR (to give a high NOx condition) while the CSF system was studied with both auto EGR and EGR off. Turning off the EGR resulted in approximately 5.0g/hp-hr engine out NOx while with auto EGR it was approximately 1.0g/hp-hr. Auto-EGR resulted in higher temperatures and lower exhausts flow as compared to EGR off as shown in Figure 1. The bars represent exhaust flow while dashed lines show SCR or SCR-DPF inlet temperatures. With EGR off, the exhaust flow increased at a minimum of 40% to over 100% in some cases. Consequently, with EGR off, exhaust temperature under these steady state conditions dropped anywhere from 30°C to over 100°C.

Figure 2 shows NOx conversion for both systems at steady state with ANR of 1.2. For the majority of modes, the SCR-DPF system has equivalent NOx conversion as the CSF system even with high engine out NOx, higher exhaust flow and lower inlet temperatures. For example under C25 test condition, the SCR-DPF demonstrated almost similar (>93%) NOx conversion as the CSF system, even though the exhaust flow was more than double

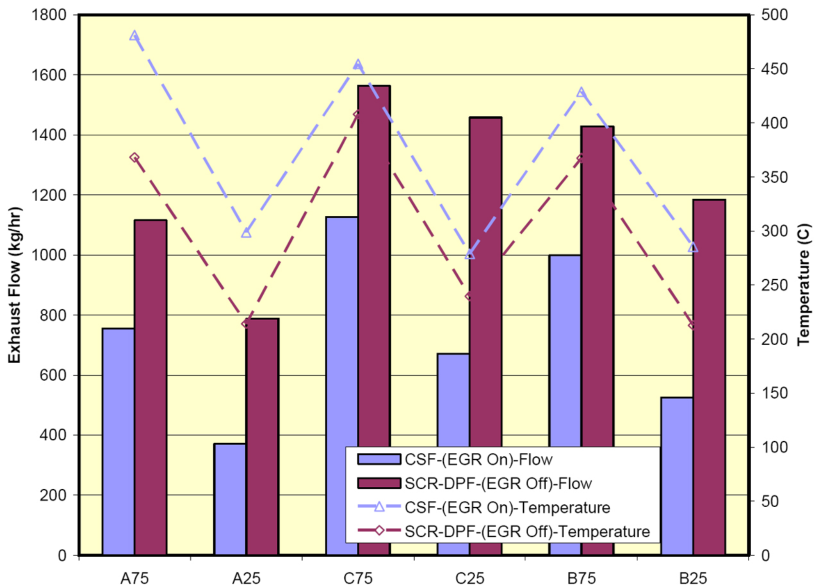


Figure 1. Exhaust flow and temperature at different engine operations

with the SCR-DPF and exhaust temperature was over 30°C lower. Only under the very low temperatures for A25 and B25, the SCR-DPF system showed lower performance than the CSF system. This is due to very low temperature experienced by the SCR-DPF, approximately 214°C as compared to 290-300°C for the CSF system. However, the overall results suggested that there is a potential to achieve higher overall NOx conversion with the SCR-DPF system than the CSF+SCR systems. This is further examined by testing both systems under similar test conditions.

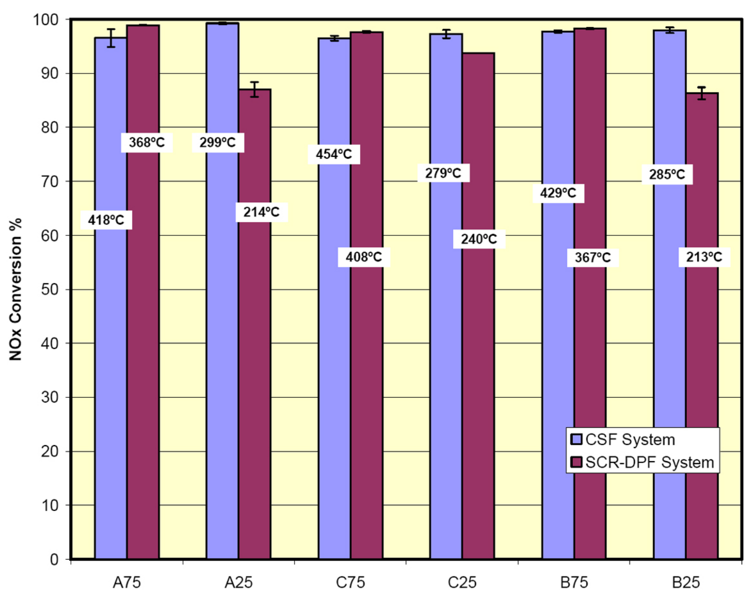


Figure 2. NOx conversion for CSF (auto-EGR) and SCR-DPF (no EGR)

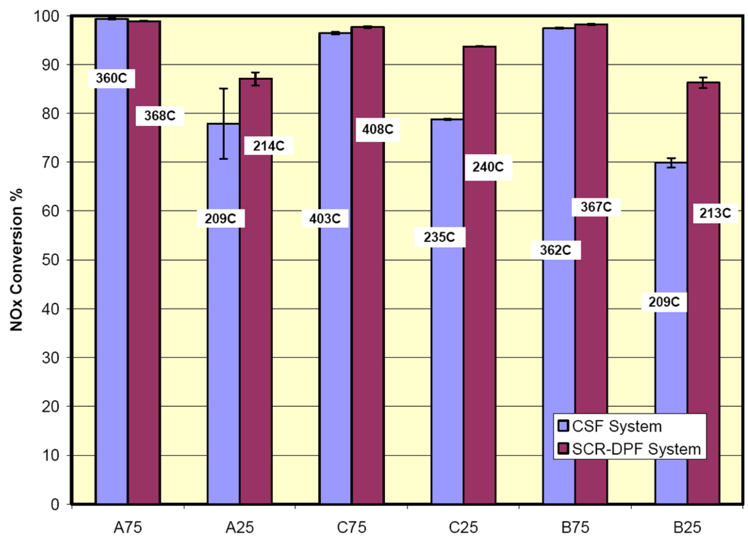


Figure 3. NOx conversion for CSF and SCR-DPF systems (no EGR)

Figure 3 shows the results of steady state testing of the CSF system versus the SCR-DPF system under similar EGR-off conditions. These tests were carried out to compare the performance of these two systems when subjected to similar temperatures and flow conditions. The exhaust flow conditions were those of the EGR-off conditions as shown in Figure 1. The exhaust temperatures at SCR inlet for each test conditions are shown in Figure 3. Note that the temperature was measured at SCR-DPF inlet for SCR-DPF system and at SCR inlet for CSF system. ANR was maintained at 1.2 for these tests. These results clearly showed the benefit in NOx reduction with the SCR-DPF system, especially under difficult low temperature conditions. Comparing A25 and B25 conditions with temperatures around 210°C, the SCR-DPF system exhibited significantly higher NOx reduction than the CSF system. Especially at B25 which had 50% higher flow than A25, the SCR-DPF system exhibited around 85% NOx reduction while the CSF system exhibited only about 70%. Similarly at C25, with even higher flow but temperatures around 237°C, the SCR-DPF system produced 93% NOx reduction while it was only 79% with the CSF system. As the temperature increased beyond 350°C, this difference was minimized.

A light-off test comparison was also conducted to determine performance of the SCR-DPF as compared to the CSF system. The experiment was designed to have similar exhaust temperatures for both systems and space velocity was maintained approximately at 30,000/hr. EGR was turned off for SCR-DPF system while CSF system was tested with auto-EGR. ANR for each point was at 1.20. Figure 4 shows temperatures for each system during these tests. As is shown, the two systems had similar temperatures for most modes except the last mode, where the CSF system experienced higher temperature.

Figure 5 shows NOx conversion for each system during light-off tests. These results suggested that the SCR-DPF system exhibits higher NOx conversion at lower temperatures from 200°C to about 280°C, as compared to the CSF system. For example, at 200°C, the SCR-DPF system produced 77% NOx conversion whereas the CSF system showed only 62%. From 280°C onward, both systems have similar NOx conversion. However, at 340°C, there appears to be a slight drop in NOx conversion with the CSF system, which was not observed with the SCR-DPF system. This data has been repeated and is being further investigated. In general, these results indicate that the SCR-DPF system has a better light-off as compared to the CSF system.

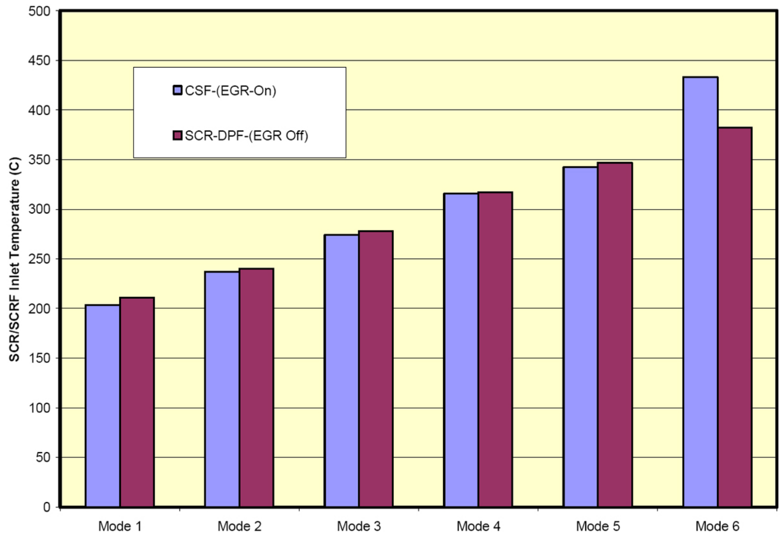


Figure 4. Exhaust temperature for SCR-DPF (EGR off) and CSF (Auto-EGR) during Light-off tests

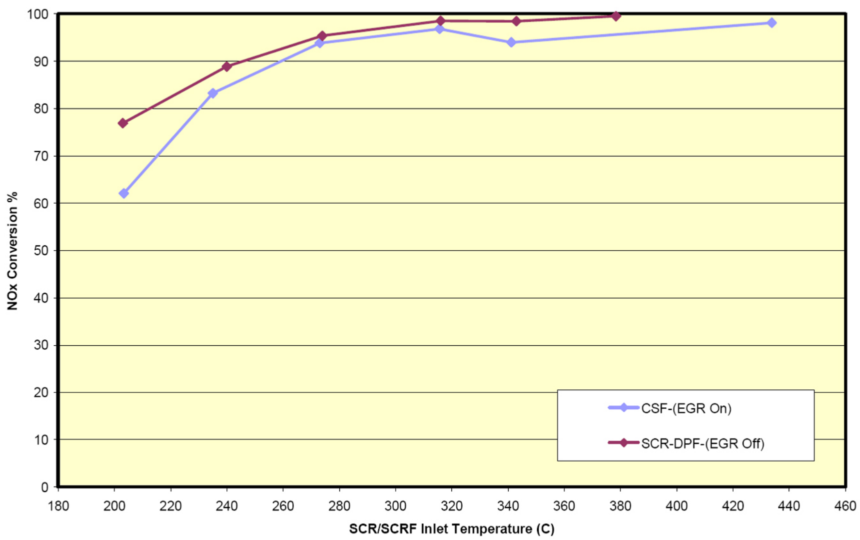


Figure 5. NOx conversion light-off comparison between SCR-DPF system (EGR off) and CSF system (Auto-EGR), ANR=1.2

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