

Investigation of NO_x- and PM-reduction by a Combination of SCR-catalyst and Diesel Particulate Filter for Heavy-duty Diesel Engine

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ABSTRACT

The upcoming Euro VI emission legislation for Heavy Duty Diesel engines can be complied with by using a combination of a wall flow DPF and a UREA SCR-system. This paper describes investigations of NO_x and PM reduction by a combination of SCR-catalyst and an (uncoated) Diesel particulate filter (DPF), performed on a fully transient heavy-duty test bench. Soot loading and passive regeneration of the DPF for different configurations of both components and active regeneration by fuel injection into the exhaust gas line were investigated. The impact of DPF on SCR-catalyst as well as SCR-catalyst impact on DPF was analyzed in terms of NO_x-conversion and regeneration efficiency of the filter under steady-state and transient operating conditions.

The NO_x-conversions for the configuration SCR-catalyst in front of DPF were higher for all operating conditions than for the combination DPF in front of SCR-catalyst. This was due to higher temperatures and higher NO₂-to-NO_x-ratios in front of the SCR-catalyst. On the other hand, passive regeneration of the filter in this configuration was poor under certain operating conditions due to low concentrations of NO₂ in front of the DPF. For the combination DPF in front of SCR-catalyst, passive regeneration of the filter was sufficient in a wide range of the operating conditions.

INTRODUCTION

The tighter emission standards to be adopted in Europe and the US in future, will require the use of aftertreatment devices to reduce both PM and NO_x-emissions from Diesel engines. Combustion improvements alone are not sufficient to achieve these emission targets. Although the Diesel particulate filter

(DPF) for reduction of PM-emissions and the urea based SCR-catalyst for lowering NO_x-emissions are already well-established technologies for heavy-duty engines [1-5] the combination of both subsystems requires further investigation in order to reach a better understanding of the interaction between SCR-catalyst and DPF [6, 7]. Placing the SCR-catalyst upstream of the DPF reduces its warm-up time, thus improving the cold start NO_x-emissions. At the same time however, the exhaust gas reaching the DPF will be poor in NO₂, thus minimizing the passive regeneration potential and increasing the active regeneration frequency. DPF placement in front of the SCR-catalyst would be ideal for its regeneration management but would pose significant problems for the SCR cold start efficiency due to large DPF thermal mass and the minimum temperature needed to start AdBlue dosing.

Some of the above mentioned design optimization issues are studied in the present paper by performing measurements on a fully transient heavy-duty test bench equipped with an aftertreatment system consisting of a combination of a SCR-catalyst and an uncatalysed Diesel particulate filter (DPF). The target of this study was to investigate the impact of the DPF on the SCR-catalyst in the configuration DPF in front of SCR-catalyst and the influence of the SCR-catalyst on the DPF in the configuration SCR-catalyst in front of the DPF.

EXPERIMENTAL METHODS

ENGINE AND SCR-CALIBRATION

For the measurements on the combined system a calibrated engine and SCR-catalyst was used. The engine was mapped by measuring the NO_x engine-out emission as a function of the engine speed and torque (exhaust gas temperature and exhaust gas flow). Based on this data the urea injection of AdBlue[®] was controlled using a

patented control algorithm (European Patent EP 0 775 013 B1, United States Patent 5,785,937). This algorithm uses the capacity of the SCR-catalyst to store and release ammonia as a function of the temperature into account.

For the measurements performed with the combination system consisting of DOC, DPF and SCR-catalyst, the SCR-catalyst was calibrated for ammonia slip minimized to a certain extent for the steady-state and transient test cycles. For recognition and capturing the impact of the combination system on the NO_x-conversion with DPF in front of the SCR-catalyst the dosing calibration for AdBlue® was kept unchanged. However, the AdBlue® quantities increased slightly due to higher temperature readings of the SCR-catalyst related temperature sensors.

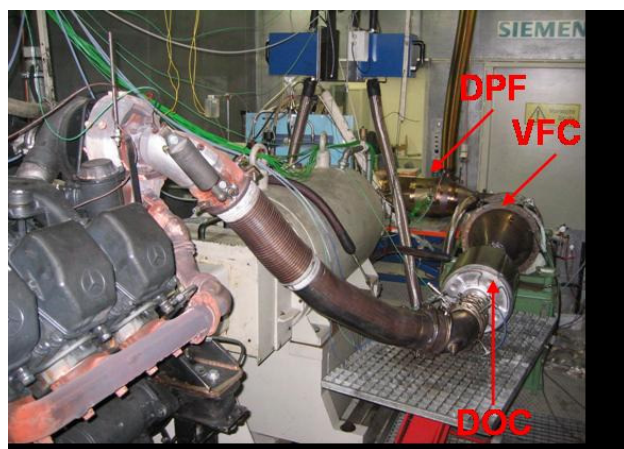
EXPERIMENTAL SETUP

Engine and test-bench

For this study a Daimler OM 501 LA engine together with a Siemens AC-dynamometer was used. This fully transient heavy-duty test-bench allows the simulation of steady-state and transient test cycles. The following table summarizes the main data of the test-engine.

Model	Daimler OM 501 LA
Configuration	V6, turbocharged
Fuel injection	Unit Injectors (PLD)
Displacement	12 L
Rated Speed	1900 rpm
Maximum Torque	2550 Nm
Maximum Power	400 hp
Emission standard	Euro II
Other features	no EGR and no post injection

Table 1: Test-Engine data



Picture 1: Test Bench set-up

For all experiments Diesel fuel according to DIN EN 590 and a content of FAME of maximum 5% was used. The sulphur content was below 10 ppm. As lube oil Shell Rimula Ultra 5W-30 with a sulphated ash content of 1.9% was utilized.

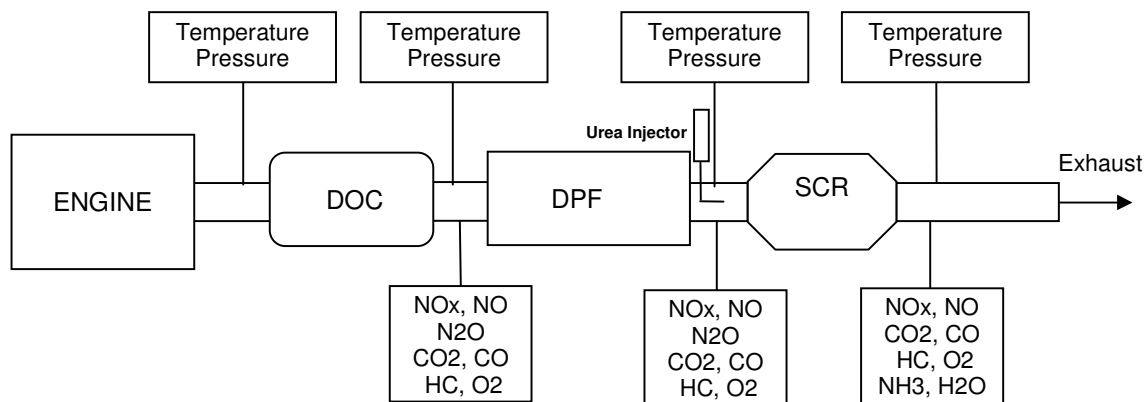
Three different configurations were used. For the evaluation of the impact of DPF on SCR-catalyst and vice versa, the combinations DOC plus DPF in front of SCR-catalyst as well as the combination DOC plus SCR-catalyst in front of DPF were applied (figure 1: configurations C1 and C2). For the active regeneration the combination DOC plus DPF in front of SCR-catalyst with an additional fuel injector (HC-doser) directly in front of the DOC was used (figure 1: configuration C3).

Diesel oxidation catalyst for NO₂-increase

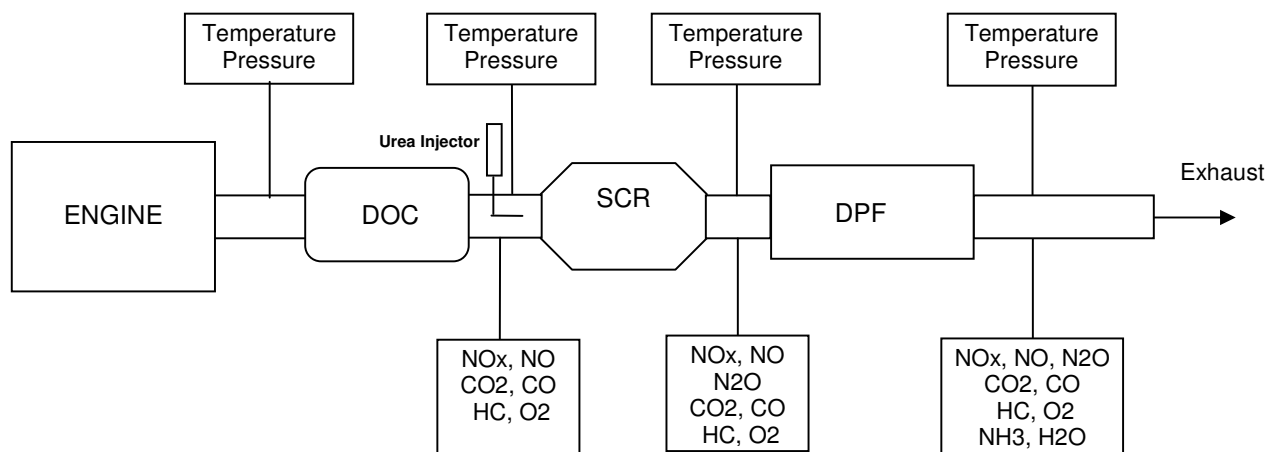
Two different oxidation catalysts were used, one for the measurements on passive regeneration of the DPF and another one for the measurements on active regeneration of the DPF. This is due to the different requirements on the oxidation catalysts. Passive regeneration only works, if the NO₂-content in front of the DPF is sufficiently high. The NO₂-content of the engine-out emission of the applied engine is between 5 and 10 percent of the total NO_x-concentration within the whole temperature range (200°C - 500°C). With a DOC connected upstream of the DPF the NO₂-content is increased in dependence of the temperature and the exhaust flow. For the oxidation catalyst used in this study the NO₂-percentage has its maximum of about 70% at a catalyst temperature of approximately 300 °C (and an exhaust flow of 700 kg/h). For lower temperature the NO₂-percentage achieves values of about 50% at 220°C, for higher temperatures the NO₂-percentage decreases down to 20% at 500°C. An increased NO₂-concentration in front of the SCR-catalyst leads to a higher NO_x-conversion [8]. Especially at lower temperatures (200 – 300°C) the NO_x-conversion is increased markedly. An increase of up to 10% in NO_x-conversions at temperatures below 350°C and of up to 5% at temperatures above 400 °C was experimentally found.

Diesel oxidation catalyst for active regeneration

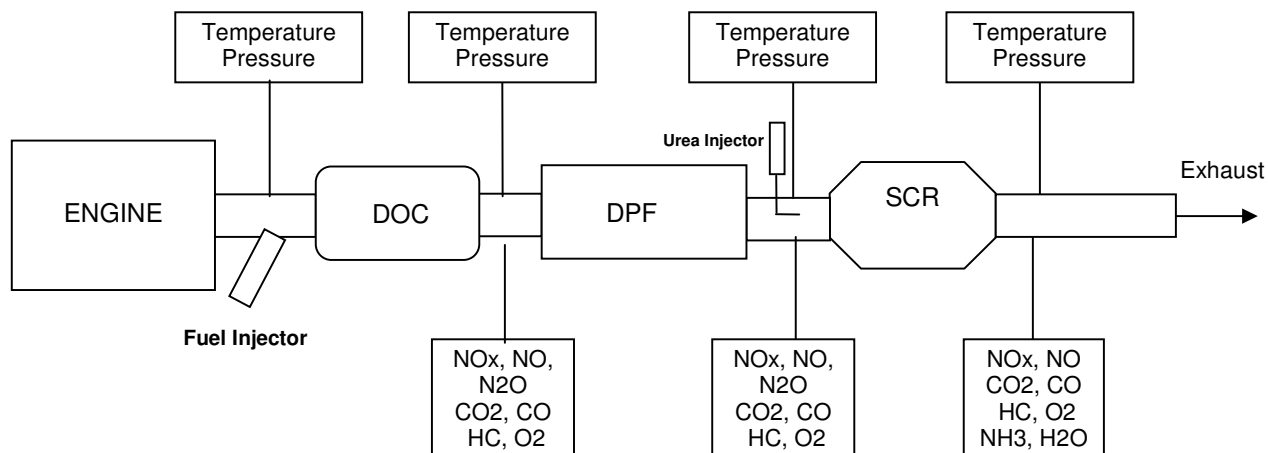
The main task of the Diesel oxidation catalyst in the case of active regeneration is the reduction of the temperature for oxidizing the injected fuel (hydrocarbons). The heat of the oxidation process leads to an increase of the temperature of the exhaust flow up to the ignition temperature for soot of about 650°C. For this purpose a metallic oxidation catalyst was available.



Configuration C1: DOC-DPF-SCR



Configuration C2: DOC-SCR-DPF



Configuration C3: DOC-DPF-SCR with additional injector (active regeneration)

Figure 1: DOC, DPF, SCR-catalyst arrangements

The following Diesel oxidation catalysts were used:

DOC	DOC1: Passive regeneration	DOC2: HC oxidation
Substrate	cordierite	metal
Cell density [cps]	300	300
Diameter [mm]	280	190
Length [mm]	150	150
Volume [l]	9.2	4.2

Table 2: Diesel Oxidation Catalysts

Diesel particulate filter

The filter used during these tests is the Saint Gobain SG3 filter made of Recrystallized Silicon Carbide (RSiC). It is defined by an asymmetrical wavy design (figure 2) [9-11] which allows an increase in ash storage capacity and reduces filter pressure drop during the soot accumulation phase. The table 3 below describes the main characteristics of the SG3 filter.

Material	Silicon carbide
Filter type	Wall flow filter
Diameter [inch]	12
Length [inch]	14
Volume [l]	25.3
Mass [kg]	16.7
Cell density [cps]	193
Wall thickness [μ m]	350
Geometry	Asymmetrical wavy
Porosity [%]	47
d50 [μ m]	15

Table 3: Main data of the Diesel Particulate Filter

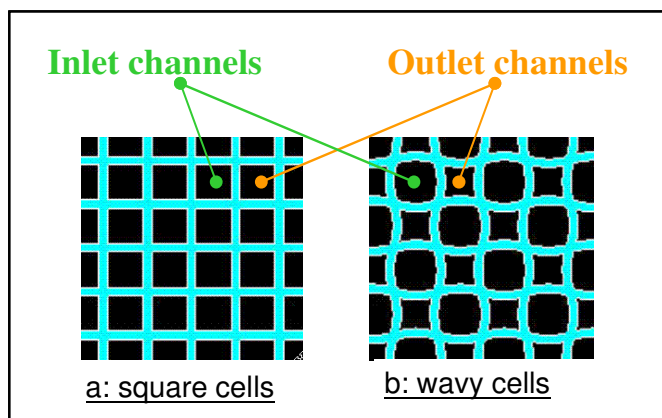


Figure 2: schematic description of 2a: standard square cell geometry and 2b: wavy cell geometry of honeycomb structures

The filter used for this study is uncatalysed (uncoated). For the measurements regarding the active regeneration 12 thermocouples were fixed within the filter to measure the temperature development and temperature distribution across the filter outlet and along the middle axis of the filter. The filter was designed for a maximum back pressure of 150 mbar at maximum soot load of about 5 g/l for an exhaust flow of 1500 kg/h and an exhaust temperature of 500 °C.

Selective-Catalytic-Reduction-Catalyst

For all experiments an Argillon, fully extruded non-aged Fe-Zeolite (VFC) with a total volume of about 9.25l was used. Three canned fully extruded honeycombs were configured in a parallel arrangement within a reactor-housing. The outside reactor was thermally insulated with insulating mats.

Material	Fe-Zeolite
Configuration	3 honeycombs (parallel)
Diameter [inch]	5.66
Length [inch]	7.5
Total Volume [l]	9.25
Cell density [cps]	300

Table 4: Main data of SCR-catalyst

As reducing agent for SCR a 32.5% urea-water solution (AdBlue®) was used. AdBlue® was injected in front of the SCR-catalyst. A mixing element between the positions of AdBlue® injection and the SCR-catalyst was installed in order to improve the mixture formation of AdBlue® and the exhaust gas for achieving a homogeneous ammonia distribution in front of the SCR-catalyst. The position of the mixer downstream of AdBlue® injection is the proper location, which was confirmed by former measurements. An air-assisted injection system supplied by Hilite® was used for dosing the reducing agent.

Additional fuel injector (HC-doser)

As additional fuel injector for the active regeneration a manifold-injector in a special adapter was fixed in the exhaust gas line in front of the DOC. The fuel was injected in front of the oxidation catalyst into the exhaust flow. The injected quantity was adjusted by a control box with a maximum injection flow of about 8 kg/h (10 l/h).

For an improved mixture formation of the injected fuel and the exhaust gas another mixing element was fixed upstream of the injector into exhaust gas line. With the mixer generated turbulences (swirl) the mixing process was enhanced and the fuel was kept off the pipe wall. The upstream position of the mixer provides not only an