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Andrew P. Walker, Ronny Allansson, Philip G. Blakeman and Mats Lavenius
Johnson Matthey, Catalytic Systems Division

Sara Erkfeldt and Henrik Landalv
Volvo Powertrain Corporation

Bill Ball and Pat Harrod
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Didier Manning and Leopold Bernegger
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ABSTRACT

The tightening of Heavy Duty Diesel (HDD) emissions legislation throughout the world is leading to the development of emission control devices to enable HDD engines to meet the new standards. NOx and Particulate Matter (PM) are the key pollutants which these emission control systems need to address. Diesel Particulate Filters (DPFs) are already in use in significant numbers to control PM emissions from HDD vehicles, and Selective Catalytic Reduction (SCR) is a very promising technology to control NOx emissions.

This paper describes the development and performance of the Compact SCR-Trap system – a pollution control device comprising a DPF-based system (the Continuously Regenerating Trap system) upstream of an SCR system. The system has been designed to be as easy to package as possible, by minimising the total volume of the system and by incorporating the SCR catalysts on annular substrates placed around the outside of the DPF-based system. This novel design gives rise to an easy-to-package emission control device capable of providing very high conversions of all four major pollutants, NOx, PM, CO and HC. The design details are discussed, and the performance of the system over both steady state and transient cycles is presented. NOx conversions of up to 92% have been demonstrated, and the system's emissions of all four pollutants are well inside the Euro V, and probably also the US 2007 limits (subject to verification of PM).

INTRODUCTION

The progressive tightening of the emissions standards for Heavy Duty Diesel vehicles throughout the world presents challenges for the engine development and emission control communities. In both Europe and North America the major challenges are in PM and NOx control for the legislation to be introduced in 2005 (Euro IV), 2007 (US '07), 2008 (Euro V), and 2010 (US '10). Table 1 summarises the evolution of the emissions standards in Europe, and Table 2 outlines the US regulations.

Table 1: Emissions Legislation Limits in Europe (ESC Test Cycle; g $kW^{-1}hr^{-1}$)

Year	HC	CO	NOx	PM
2000 (Euro III)	0.66	2.1	5.0	0.10
2005 (Euro IV)	0.46	1.5	3.5	0.02
2008 (Euro V)	0.25	1.5	2.0	0.02

Table 2: Emissions Legislation Limits the US (SET Test Cycle and US HDT Cycle; g $bhp^{-1}hr^{-1}$)
(Note that 1 g $bhp^{-1}hr^{-1}$ = 1.341 g $kW^{-1}hr^{-1}$)

Year	HC	CO	NOx	PM
1998	1.3	15.5	4.0	0.10
2004	0.5	15.5	2.5	0.10
2007	0.14	15.5	1.2	0.01
2010	0.14	15.5	0.2	0.01

The HC and CO emission limits are not expected to cause significant problems, because the engine-out emissions of these pollutants are already very low. However, major reductions in both PM and NOx emissions are required in the near future.

One system which has shown great promise in controlling PM emissions is the Continuously Regenerating Trap (CRT®, developed and patented by Johnson Matthey [1]). Throughout the remainder of this paper, this system will be referred to as the Continuously Regenerating Diesel Particulate Filter, CR-DPF. There are currently over 35,000 CR-DPF systems in operation throughout the world, and the long-term field durability of the system has been clearly demonstrated [2]. Indeed, systems have been shown to provide very high levels of CO, HC and PM reduction even after over 500,000 km (and six years) of field operation [3].

The CR-DPF system comprises an oxidation catalyst followed by a wall-flow Diesel Particulate Filter (DPF). The DPF traps the PM and the oxidation catalyst oxidises a portion of the engine-out NO to generate NO_2. This NO_2 combusts the PM at a much lower temperature (around 250°C) than does oxygen (around 550°C). This low temperature combustion of PM by NO_2 enables the passive operation (with continuous PM removal) of the CR-DPF system on a wide range of HDD applications (eg buses, trucks, garbage trucks) and is the basis of the CR-DPF. The CR-DPF has been used very successfully in the retrofit market over a wide range of operating duty cycles, since most HDD applications have duty cycles which are sufficiently warm to guarantee continuous regeneration of the CR-DPF system.

The oxidation catalyst used within the CR-DPF is optimised to generate appropriate levels of NO_2 to enable continuous, passive PM regeneration. This catalyst is also very effective at oxidising CO (into CO_2) and HC (into CO_2 and H_2O), so the system provides very high conversions of PM, HC and CO. However, when the NO_2 generated by the oxidation catalyst reacts with carbon it is converted back into NO, so very little NOx conversion is observed over the CR-DPF system.

As discussed above, high conversions of NOx are required within the pollution control systems of the future. The most effective on-board NOx reduction strategy for HDD vehicles is Selective Catalytic Reduction (SCR) [4], so this was the approach used to control NOx emissions in this work. SCR systems reduce NOx via reaction with ammonia; this reaction is highly selective even in environments containing excess oxygen, such as the exhaust of Diesel vehicles:

$$4\ NH_3 + 4\ NO + O_2 \rightarrow 4\ N_2 + 6\ H_2O \qquad (1)$$

Ammonia is generated on board the vehicle via the rapid hydrolysis of urea. One of the keys to the successful implementation of SCR technology is the ability to match the amount of urea injected to the amount of NOx emitted from the engine. While it is possible to do this using on-board NOx sensors [5], the more common approach is to map the NOx emissions of the engine, and to inject urea based on the information contained in these maps. The latter was the approach used here.

The very effective combination of the CR-DPF (for PM, HC and CO control) with an SCR system (for NOx control) has previously been demonstrated [6]. This SCRT™ system was shown to give very high conversions of all four major pollutants over the ESC: up to 85% NOx, 96% PM, 98% HC and 100% CO conversion, using a total system volume of 51 litres on a 12 litre engine calibrated to the Euro 1 emissions standards. This catalyst system will be referred to as the SCR-Trap System for the remainder of this paper.

In this earlier work, the combined system was arranged with the CR-DPF in front of the SCR system. Within this configuration, the CR-DPF removes CO, HC and PM, and converts some of the engine-out NO into NO_2, before the gas passes to the SCR system. This leads to a large improvement in the low temperature NOx conversion of the SCR catalysts, partly because both CO and HC can inhibit the low temperature performance of SCR catalysts, but mainly because the presence of NO_2 in the gas stream strongly promotes low temperature SCR activity [6, 7]. This promotion occurs via the very fast reaction:

$$2\ NH_3 + NO + NO_2 \rightarrow 2\ N_2 + 3\ H_2O \qquad (2)$$

Furthermore, the removal of the PM upstream of the SCR system removes the possibility of PM fouling of the SCR catalysts and the urea injection system. So clear synergies were demonstrated for this combined system.

In this earlier work, the combined system was arranged in a linear configuration. Such an arrangement will be suitable for many HDD vehicles, especially buses. However, for many trucks a more compact arrangement would be superior, and therefore the alternative layout shown in Figure 1 was developed.

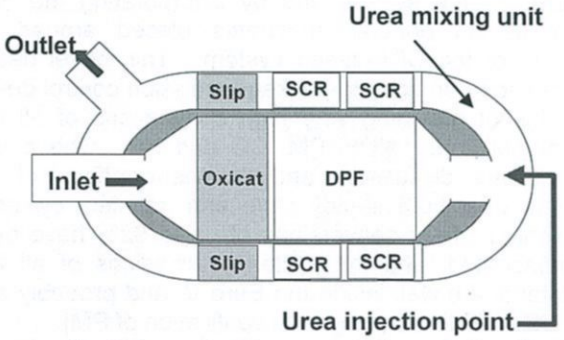

Figure 1: Schematic Representation of the Compact SCRT™ Concept

Within this design the gas first passes through the CR-DPF system, and is then turned through 180° and flowed through the SCR catalysts, which are coated onto

metallic, annular substrates, fitted around the CR-DPF system. This presents a wider but much shorter packaging envelope for the combined system, and this system will be referred to as the Compact SCR-Trap System for the rest of this paper.

DEVELOPMENT OBJECTIVES

A project was therefore started to verify that this technology did in fact have the potential to meet US 2007 and Euro V emissions levels, when realized in practical form. The chosen means of verification was to culminate in an extensive field test on heavy trucks engaged in regional distribution duties in the US. This meant that the SCR-Trap systems were to be developed to meet typical vehicle installation and operating constraints.

This paper describes the development of the Compact SCR-Trap system for this purpose, and outlines its performance over both the ESC and the US Heavy Duty Transient test cycles, on a Volvo D12C, US'00 12 litre engine.

COMPACT SYSTEM DESIGN

REQUIREMENTS

The concept of Figure 1 had to be realised in a practical design meeting a number of constraints. Key targets were:

- to fit the unit within the specified space envelope 620x600x620mm (24.4x23.6x24.4in) available on the test vehicle, and to match the existing inlet and outlet pipe positions of the standard muffler
- to enable both the CR-DPF filter and the urea injector to be easily removed for servicing
- to meet a backpressure limit of 20kPa at a flow of 0.5 kg/s, 438°C (2.9 psi @ 1.1 lb/s, 820°F)
- to achieve the structural integrity and durability required for a 2-year 350,000 km (220,000 mile) field trial, with service intervals of at least 50,000km (31,250 miles)
- to meet specified noise and emissions limits

In addition, it was the clear intention of all the project partners to have a design which was functionally as close to a future production system as possible.

OVERALL LAYOUT

Designs with a range of alternative catalyst and filter sizes which could be fitted within the available space were assessed for the best compromise between backpressure (with filter clean and after accumulating ash), thermal mass and weight while achieving the space velocities estimated to be required for satisfactory catalyst performance. This resulted in the choice of nominal sizes as follows:

CR-DPF catalyst (diameter x length): 381 x 74.6 mm (15 x 2.94 in)

Filter (diameter x length): 381 x 305 mm (15 x 12 in)

SCR catalysts (2 off) + ammonia slip catalyst (1 off): each of inner diameter 408.5 mm (16.08 in), outer diameter 575 mm (22.64 in), and length 74.6 mm (2.93 in),

So within a total length of 620mm there had to be accommodated CR-DPF elements with a combined length of 380mm and SCR/ammonia slip catalysts of combined length 224mm (all before canning), as well as room for the inlet and outlet flows, the urea mixing section, and thermally-insulated endcaps. A major design challenge was therefore achieving the length constraint while minimising pressure losses within the unit.

KEY DESIGN FEATURES

Unlike the schematic representation of Figure 1, both inlet and outlet pipes had to be oriented in a radial direction. The length constraint was met by overlapping the pipes in an axial direction, and separating the inlet and outlet flows by means of a partition across the outer annulus [8]. The inlet and outlet are separated angularly by only 66 degrees, which adds to the difficulty of achieving low pressure losses and uniform flow through the catalysts. The CR-DPF is supported by a central tube, which locates on both endcaps. The tube contains apertures which allow the flow through it from the inlet to the CR-DPF and from the CR-DPF to the SCR section. Loads are transferred to this tube from the mountings via the partition and a support strut assembly. The latter avoids significant loads being transferred through the SCR catalysts, which for the field trial units have been made removable. This removability also necessitated the incorporation of inner and outer seals to prevent flow bypassing these catalysts, which is particularly important to minimise ammonia slip and to maximise NOx conversion. It also required careful design to overcome problems of radial tolerance build-up. The filter and the CR-DPF catalyst are retained axially by a removable retention device inside the central tube [8]. To clean out incombustible residues from the filter, it can be removed by first removing the mixer assembly and then the retention device, each requiring the release of only a single fastener; the filter is then withdrawn using a special tool.

The urea is injected from a centrally-positioned injector. Mixing of the urea with the exhaust gas stream occurs in a mixing unit downstream of the injector [8]. The distance from the end of the filter to the inside of the endcap is only 127mm (5 in), but the mixer achieves

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