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Novel base metal-palladium catalytic diesel filter coating with NO_2 reducing properties

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ABSTRACT

A novel base metal-palladium catalytic coating was applied on commercial silicon carbide wall flow diesel filters and tested in an engine test bench. This catalytic coating limits the NO_2 formation and even removes NO_2 within a wide temperature range. Soot combustion, HC conversion and CO conversion properties are comparable to current platinum-based coatings, but at a lower cost. This paper compares the results from engine bench tests of present commercial solutions as regards NO_2-, HC-, CO-removal and soot combustion with the novel coating. Furthermore, emission test results from base metal-palladium coated diesel particulate filters installed on operating taxis and related test cycle data are presented. A significant reduction in NO_2 emission compared to present technology is measured.

INTRODUCTION

The diesel particulate wall flow filter (DPF) is today recognized as being the most effective way of reducing not only the mass but also the number of emitted particles from diesel-fuelled vehicles. In order to facilitate a reliable DPF regeneration by combustion of accumulated soot and simultaneously remove hydrocarbons and carbon monoxide, the DPF must be provided with a catalytic coating. One of the technical solutions has been to utilize NO_2 as low-temperature soot oxidation agent [1]. The NO_2 for this reaction is obtained by oxidizing a large part of the NO present in the exhaust gas by applying a Pt-containing diesel oxidation catalyst (DOC) in front of the DPF as well as a Pt catalyst coating on the DPF. However, since the NO_2/soot ratio is difficult to manage in practice, a surplus of NO_2 relating to soot combustion is formed, resulting in an increased NO_2 emission from the vehicles.

Soot combustion by NO_2 is mostly responsible for the so-called passive soot regeneration that takes place during normal driving. A way to quantify the passive soot combustion is by the so-called balance point temperature (BPT), which is the temperature at which soot accumulation on the filter is balanced by soot combustion. Soot oxidation by NO_2 has been reported to result in a BPT as low as 250°C [1], which is sufficient to rely only on passive regeneration of the soot during many driving patterns. However, the BPT is highly dependent on engine, test protocol and exhaust composition, and most often forced regeneration of the filter is also required.

Forced regeneration is obtained by actively increasing the temperature in the filter to more than 600°C whenever the pressure drop over the filter exceeds a tolerable pressure drop limit corresponding to a maximum soot load, typically 5-8 g soot/l. This high temperature is normally achieved by diesel post injection into the engine.

In general, the role of the catalytic coating on a diesel particulate filter is to assist soot burning either by forming more NO_2 or by catalyzing the oxidation of soot. In addition the catalytic coating has the function of combusting hydrocarbons and carbon monoxide both under passive and forced regeneration.

Concern is now being expressed about the NO_2 formation over Pt coatings and the ensuing NO_2 emissions from vehicles equipped with such devices. NO_2 is more toxic than NO, and the limit of 40 μg/m^3 of NO_2 which will be required by the European Union from 2010 in city streets [2] is today significantly surpassed in many cities [3]. Therefore, alternatives are required. Furthermore, these filter coatings are expensive due to the high cost of Pt [4].

A way to avoid these drawbacks is to develop alternative catalytic coating formulations that reduce the NO_2 emission from the DPF and preferably also the precious metal cost, but still possessing comparable soot, hydrocarbon (HC) and carbon monoxide (CO) combustion properties.

Pd is currently significantly cheaper than Pt, it has a low tendency to catalyze the oxidation of NO to NO_2 while having nearly the same potential for catalyzing the full oxidation of HC and CO.

The passive soot regeneration by generated NO_2, taking place during the normal exhaust temperatures, can to some extent be replaced by a catalytic base metal coating on the diesel filter. It implies that passive soot regeneration can take place by a base metal catalyst on the filter without the assistance of NO_2. However, this requires that a good soot base metal catalyst contact is facilitated by proper design of the catalyzed filter. It has been shown that a base metal catalyst on the filter has the potential for an increased soot combustion rate at temperatures above 350°C [5].

This knowledge was used in our development of the novel base metal-palladium coating described in the current paper. As evidenced, this coat does not only produce extra NO_2 but it reduces significant amounts of NO_2 to NO at temperatures below 330°C, which makes the coat especially usable in connection with a normal Pt-DOC in front of the filter.

EXPERIMENTAL – ENGINE TEST BENCH

CATALYST PREPARATION

A series of commercial silicon carbide wall flow filters of 46.5 cells/cm^2 with wall thickness of 0.31 mm and 0.25 mm with the geometric dimensions (given as diameter×length) 144 mm×178 mm (2.89 l) and 144 mm×203 mm (3.30 l) were used for the experiments. The filter samples were coated with 70 g/l of this novel base metal-palladium catalytic coating according to a patent application [6]. This catalytic coating is termed BMC-211. The Pd content was 1.5 g Pd/l.

ENGINE TEST BENCH SETUP

The filters were tested in an engine test bench setup built around a 50 kW Citroën C2 1.4 HDI engine from 2004. This engine was chosen to be a representative, modern, light-duty diesel engine. Due to its high injection pressure (1600 bar) it produces dry soot of a small size distribution which is expected to be the hardest kind of soot to regenerate in the filter.

The engine load is performed with a Schenck W150 eddy current dynamometer which is controlled by a constant speed controller by Schenck. A torque controller by Schenck and a servo motor control the accelerator pedal potentiometer with feedback from the torque measurements to ensure constant torque. The set points for both engine speed and torque are operated from a Schenck time pattern control. Thus, the test protocol can be carried out with a high level of automatization and reproducibility.

A flexible exhaust system has been constructed to facilitate replacement of DPFs and DOCs (optional) of different sizes. It also offers various choices of pressure transducer connections and plenty of thermocouple connections to measure temperature before, after and at different locations inside the DPF and DOC simultaneously. All data are logged on a computer with National Instrument data acquisition cards and Lab View software.

To perform forced regeneration of DPFs, a Purefi injection system is used to add diesel to the exhaust gas right after the turbo. The amount of diesel injected is controlled by feedback from the gas temperature right after the DOC to a predetermined temperature.

Right after the DPF, a partial stream of hot and undiluted exhaust gas is sampled through a heated sampling unit to hot analyzers: Rosemount 402 HC analyzer and Rosemount 955 NO/NO_x analyzer. A cooled stream is led to cold analyzers: Rosemount Binos 1001 CO/CO_2 analyzer and Rosemount 951A NO/NO_x analyzer. The cold NO/NO_x analyzer is used for backup and continuous validation of the hot analyzer. The analyzers are calibrated before and after the test with pure N_2 as zero gas and a certified span gas consisting of 51.3 ppm propane, 1770 ppm NO, 10.1% CO_2, 0.994% CO in N_2. All analyzer outputs are also logged on the computer. Standard diesel fuel with 15 ppm sulfur is used.

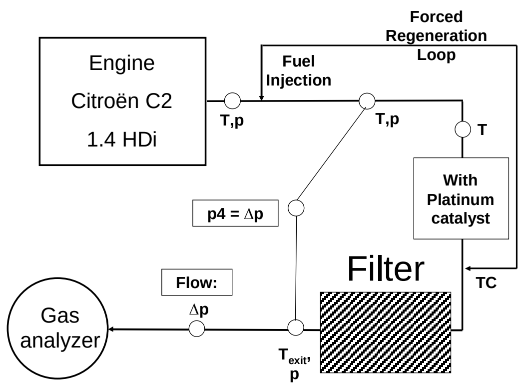

Figure 1. Engine test bench set-up

<u>Test protocol for determining soot BPT</u>

For determination of the soot balance point temperature, BPT, the filter is mounted without a DOC. The engine speed is kept constant at 2500 rpm. The engine load is increased in steps of 7 Nm from 28 to 114 Nm and finally to full load: 120 Nm. The BPT test is followed by a soot loading sequence. The load is decreased to 28, 21 and further to 14 Nm, subsequently increased and kept at 28 for 180 min. to fill the filter with 8 g/l soot. HC, CO, NO and NO_x are measured continuously.

The test protocol for filling the filter with soot is followed by forced regeneration. A DOC is mounted in front of the filter. The engine speed is kept at 2500 rpm at 28 Nm. After 30 min., the diesel injection system is switched on at a set point of 580°C. The injection is maintained for 15 min. and then changed to 850°C. The diesel injection is maintained for 10 min.

For comparison, measurements were carried out on a traditional Pt-coated silicon carbide filter with Pt load 1.5 g Pt/l, 28 cells/cm^2, 144 mm×203 mm with wall thickness 0.25 mm, (3.3 liter).

When the BPT is identified a special long time cycle is run at this temperature to verify that the soot is actually being removed.

NO_2 REDUCTION

Figure 2 shows the NO_2 emissions in engine bench experiments where the Pt-DOC is used in front of three different filters: a filter with a BMC-211 coating, the filter with the commercial Pt coating and a filter without coating. It should be noted that the soot load in the different filters is comparable in these experiments. Since NO_2 reacts with soot directly, this is important for reaching a conclusion about the effect on the NO_2 emission of the different coatings.

From Figure 2 it is evident that the BMC-211 coating removes NO_2 below a filter temperature of 330°C since the NO_2 emission is lower than for the filter without coating. At higher temperatures there is no significant difference between the NO_2 emissions from the BMC-211 coating and the uncoated filter. It is also clear that the NO_2 emission from the BMC-211 coating is significantly lower than from the Pt-containing coating at all temperatures.

It is of course very interesting to find out the mechanism behind this surprising NO_2 reduction property of the BMC-211 coating. The detailed mechanism is now under investigation. A simple base metal coating does not show this NO_2 removal effect. Preliminary results obtained with synthetic exhaust gas show that the coating efficiently catalyzes the reaction $CO + NO_2 \rightarrow CO_2 + NO$ in which CO originates from soot combustion. We will continue these investigations to elucidate the exact mechanism of NO_2 removal by the BMC-211 coating, the result of which will be reported in a separate paper.

It is clear from Figure 2 that the effect of the BMC-211 coating on NO_2 emissions over a driving cycle is very sensitive to the temperatures experienced in the filter during the specific cycle. We will return to this below. It is evident, however, that a Pt coating leads to higher NO_2 emissions than the BMC coating at all filter temperatures and, therefore, in all driving cycles.

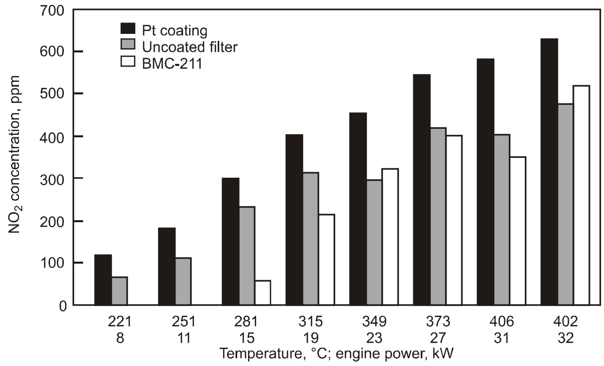

Figure 2. NO_2 emissions as a function of temperature at the exit of filter for Pt coating, uncoated and BMC-211 coating

HC AND CO CONVERSION

In the following, the conversion of CO and HC over the BMC-211 filter coating is described. The measurements were carried out without a DOC in front of the filter. The conversion over a coated filter is in all cases determined relative to an uncoated filter; meaning that the conversion of component A, X_A, is determined as

$$X_A = 100\left(1 - \frac{C_A}{C_A^{UN}}\right)[\%]$$

where C_A and C_A^{UN} are the concentrations of component A in the exhaust after the coated and uncoated filter, respectively.

From the BPT and filling test protocol, the hydrocarbon conversion as a function of filter outlet temperature is shown in Figure 3. A conversion curve for BMC-211 is fitted from three measurement series on different filters in order to test the reproducibility. The measurements show that the catalyst coating has a significant HC reduction at relevant diesel exhaust temperatures. In the following we used the temperature at which 50% conversion was obtained, T_{50}, to characterize the oxidation reactions. As seen in Figure 3, T_{50} (HC) ≈ 190ºC was obtained.

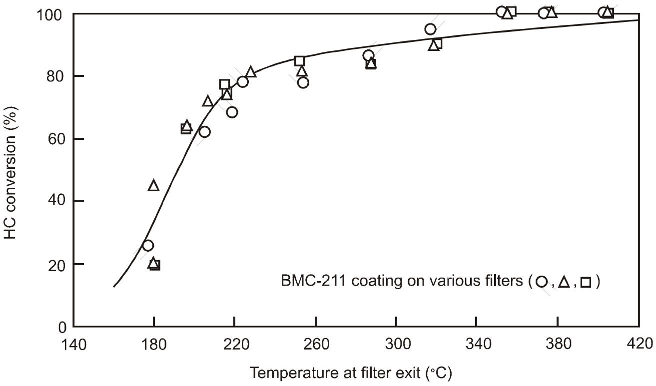

Figure 3. HC conversion in BMC-211 coated filter as a function of temperature at filter exit. The conversion is determined relative to the HC concentration out of an uncoated filter

Table 1: T_{50} values for different catalytic coatings

Coating	T50 (HC)	T50 (CO)
BMC-211	190°C	190°C
1.5 g Pt/L (commercial)	190°C	190°C
BMC-211 (after 1000°C)	220°C	220°C

Table 1 shows more T50 values determined in the same way as in Figure 3. With respect to both CO and HC oxidation, the Pd-containing coating, BMC-211, is comparable to the coating based on Pt. The T50 values obtained for the BMC-211 coating after uncontrolled soot burn-out regeneration, where the filter exit reached a peak temperature of 1000°C, show the thermal stability of the coating.

CO and HC emissions during forced regeneration

In commercial systems a DOC catalyst is most often mounted in front of a catalyzed particulate filter (pre-DOC). The DOC will oxidize HC and CO emitted by the engine during the normal driving cycle. However, secondary emissions of CO and HC occurring during filter regeneration cannot, for obvious reasons, be removed by the DOC, and it is one of the goals of the catalytic filter coating to remove these components. The ability of the Pd-based coating to remove this secondary emission was tested during a forced regeneration at a filter inlet temperature of 580°C. As described in the experimental section, the high temperature was obtained by oxidizing injected diesel over the DOC. The results are shown in Figures 4 and 5 and compared with the emissions during a similar regeneration of an uncoated filter. The HC emissions are shown in Figure 4a. A peak of 70 ppm HC is seen at about 30-33 min., when the soot burning is fastest.

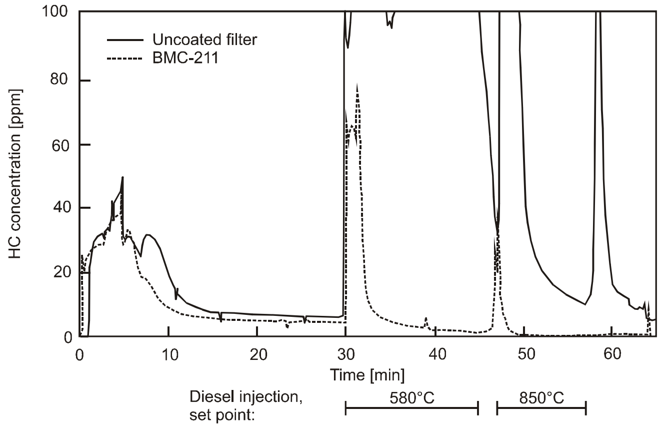

Figure 4a. HC emission during forced regeneration with/without BMC-211

The HC emission must be compared with the result of a forced regeneration on an uncoated filter at the inlet temperature where the HC emission is measured to be above 200 ppm out of range for more than 15 min., included in Figure 4a. These measurements confirm that the base metal-palladium coating gives a significant reduction of HC (>90%) during forced regeneration. Pt-coated filters give similar hydrocarbon conversions as shown in Figure 4b.

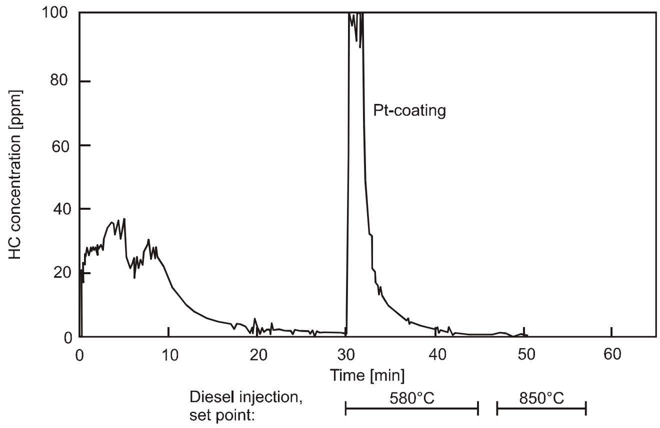

Figure 4b. HC emission during forced regeneration of commercial Pt-coated filter

Parallel results for CO emission during forced regeneration tests are shown in Figure 5. A very small peak of 50 ppm CO is seen at around 31 min. The CO_2 emission is seen to increase after 30 min. when the forced regeneration starts with additional diesel injection over the pre-DOC.

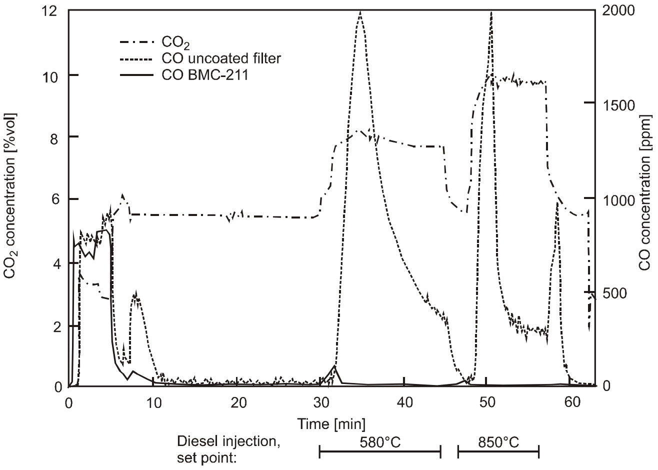

Figure 5. CO and CO_2 emission during forced regeneration with/without BMC-211

The CO emission during the forced regeneration of an uncoated filter at the same filter inlet temperature, peaks up to 2000 ppm CO and lasts again more than 10 min. These measurements confirm that the base metal-palladium coating gives a significant CO reduction (>95%) during forced regeneration. A Pt-coated filter gives similar results.

SOOT COMBUSTION

Passive soot regeneration without pre-DOC

During the test protocol for soot BPT, the pressure drop at different loads of the engine was measured on an uncoated silicon carbide filter, commercial Pt-coated and compared with the same filter type coated with the novel base metal-palladium coating.

From Figure 6 we obtain a BPT = 400ºC for BMC-211. This implies that at this temperature the amount of soot is combusted at the same rate as the new amount of soot laid down on the filter. 175 ppm NO_2 at filter exit is measured at 400ºC. When an uncoated filter is tested in a similar way, the BPT is measured to be above 440ºC, which is the maximum temperature of the engine at 2500 rpm signifying the influence of the catalytic coating on passive regeneration. For a commercial Pt-coated filter we obtain BPT = 375ºC, see results in Table 2. The difference in pressure drop seen in Figure 6 is due to the different coat amounts.

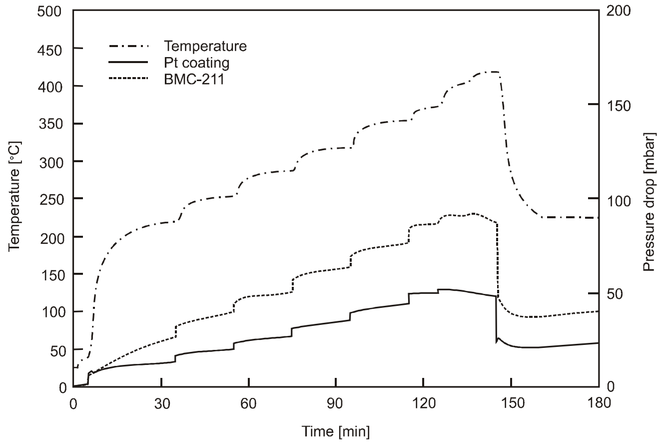

Figure 6. Balance Point Temperature test of BMC-211 (BPT=400°C) and Pt-coated filter (BPT=375°C) without pre-DOC

Table 2. BPT for BMC-211, commercial Pt coating and uncoated including NO_2 filter outlet with and without pre-DOC

Coating	BPT °C	NO_2 Outlet ppm
Pre-DOC + BMC-211	286	75
Pre-DOC + Commercial 1.5 g Pt/l	313	400
Pre-DOC + Uncoated	312	300
BMC-211	400	175
Uncoated	>400	>275
Commercial 1.5 g Pt/l	375	365
BMC-211 Burn-out at 1000°C	400	275

The passive regeneration by the base metal catalyst maintained at the balance point temperature over longer time is shown in Figure 7, where the time at the engine load resulting in ~400°C filter exit temperature is extended to 30 min.

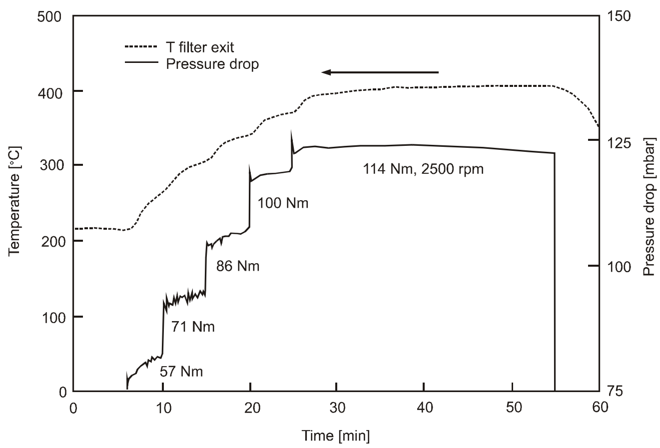

Figure 7. Soot-filled filter (BMC-211) at 400°C for 30 min. to verify the burning of soot at BPT without pre-DOC

Passive soot regeneration with pre-DOC

As already mentioned, a pre-DOC is often placed upstream of the particulate filter. NO is oxidized to NO_2 over this pre-DOC and this will of course influence the passive regeneration of the filter. The balance point was, therefore, measured with a Pt-based pre-DOC in front of the different filters. The data for this pre-DOC were 4.2 g Pt/l, 31 cells/cm^2 and Ø 136 mm×L 100 mm. The results are also presented in Table 2. The pre-DOC gives rise to a significant reduction in the balance point temperature for all the filters due to a higher NO_2 concentration. In these experiments we see no beneficial effect of Pt in the filter when comparing with the uncoated filter. With experimental uncertainty no difference in BPT is seen with the Pt coating. This is probably due to a different distribution of soot inside and outside the filter wall in the coated and uncoated filter. Combining the BMC-211 coated filter with a pre-DOC apparently has a positive effect on both passive soot combustion and NO_2 emission. The reason for this is the catalytic effect of the coating on the NO_2-assisted soot oxidation.

Forced soot regeneration

The base metal-palladium filter was repeatedly filled with 7–8 g soot/l according to the test protocol given above and was regenerated with the forced regeneration procedure at a filter inlet temperature of 580ºC. The fourth soot burn-out for BMC-211 with 7.3 g soot/l is given in Figure 8. The pressure drop over the filter during regeneration as well as engine and filter exit temperatures are shown versus time. As shown, the temperature was increased to a filter inlet temperature of 580ºC for about 15 min. and the filter was nearly fully regenerated. The filter exit temperature peaks swiftly at 711ºC as the pressure drop falls steeply at about 33 min. Complete regeneration was further confirmed by increasing the filter inlet temperature to 850ºC which gave no further significant pressure drop reduction. From this experiment it is seen that a forced regeneration can be carried out with the novel coating at 580ºC filter inlet temperature in about 15 min.

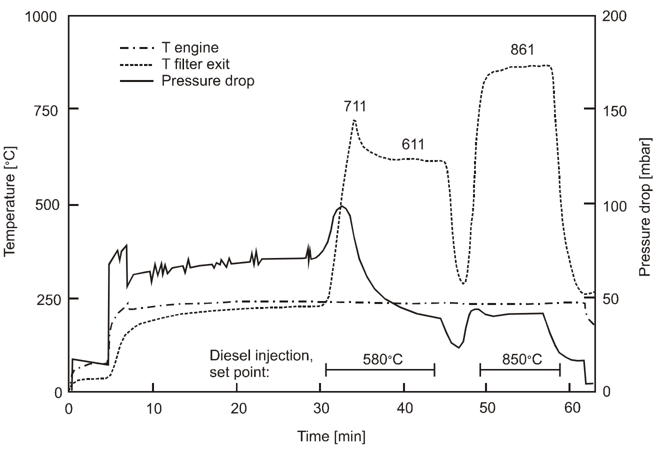

Figure 8. Forced regeneration of BMC-211 filter loaded with 7.3 g soot/l. Set-point temperature is measured at filter inlet

This forced regeneration of soot placed as a cake in the filter mostly takes place by direct oxidation of the soot. Therefore, the forced regeneration of an uncoated and a catalyzed filter does not differ significantly. However, a temperature increase of 40ºC over the filter is observed due to HC and CO conversion over the coated filter as the filter exit temperature is measured to be 611°C compared to 571°C on the uncoated filter. Such a temperature increase can potentially be utilized to decrease the filter inlet temperature to 550°C.

HEAT RESISTANCE INVESTIGATION

In one of our experiments, the filter was in an uncontrolled way filled with 10 g soot/l and a forced regeneration started according to the test protocol. The soot load during soot burn-out was so high that a peak exit temperature of the filter was measured to be 1000°C. The CO conversion performance versus temperature was measured before and after this high temperature burn-out. The results are reported in Table 1. The base metal-palladium coating still has a high conversion of CO at low temperatures. We measured that T_{50}(CO) had changed from 190°C to 220°C, an increase of 30ºC due to thermal ageing. The results for HC conversion were similar. There was no influence of the 1000ºC excursion on the soot balance point.

SULFUR RESISTANCE

Sulfur resistance is always an issue to be investigated for Pd-containing oxidation catalyst even though the sulfur content in diesel fuel will soon be below 10 ppm. We have so far not seen any influence of sulfur on the balance point temperature for BMC-211. There is a small influence on T_{50}(CO) and T_{50}(HC) but experiments also show that most of the absorbed sulfur oxides are released again during forced regeneration.

EXPERIMENTAL – TAXI FLEET TEST

INSTALLATION ON DIFFERENT REGENERATION SYSTEMS

Several diesel filter systems are already introduced in passenger car models. According to Dorenkamp, Vogt, Punke, Pfeifer and Hong [7],[8],[9],[10],[11] the four most interesting filter regeneration systems can be described as illustrated in Figure 9. Three of the systems use engine diesel post injection and a pre-DOC function to raise the temperature for forced regeneration. In the fourth solution, the pre-DOC is integrated into the filter.

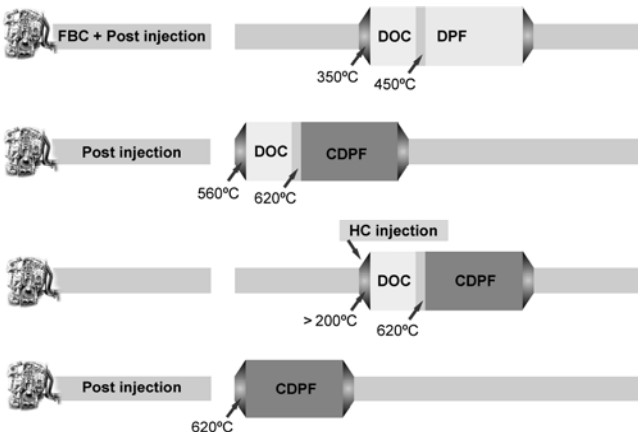

Figure 9. Diesel filter system Layouts

The engine exit temperature after the turbocharger can be 170ºC at idle and up to 620ºC with post injection. Critical exhaust temperatures to be reached are minimum 200ºC for starting the pre-DOC and 300ºC for obtaining passive regeneration. By using post injection in the engine, the engine exit temperatures can be raised to the desired values of 350ºC or 620ºC.

The first system uses fuel-borne catalyst (FBC) in the diesel for soot combustion. The soot will start to combust above 400ºC and a forced regeneration is started by increasing the engine exit temperature to 350ºC by post-injection and further increase to filter inlet temperature at 450^{o}C by HC conversion over the pre-DOC. Since the fuel-borne catalyst is inside all soot particles, the filter will be regenerated fully in less than 10 min., when a forced regeneration has been started. Today, the filter is not coated with a catalyst. A base metal-palladium coating on the filter has the potential to improve the NO_2 emission according to Figure 2 and has the potential to improve HC and CO emission during the regeneration according to Figures 4 and 5 as performed in this study, and the results for a Citroën taxi are given in Table 3.

The second system consists of a closely coupled Pt-containing pre-DOC followed by a catalyzed DPF. Today, the filter catalyst is Pt. The pre-DOC converts NO to NO_2 for the passive regeneration that takes place above 300ºC. When forced regeneration is needed, extra diesel is post-injected into all cylinders, and the engine exit temperature is raised to about 560ºC. The DOC is mounted closely coupled to the engine and tightly together with the CDPF in order to limit heat loss and gives a higher percentage of time above 300ºC for passive regeneration. During forced regeneration, the conversion of extra HC in the exhaust over the DOC increases the temperature from 560^{o}C to 620^{o}C at the inlet of the filter. The CDPF can also be mounted underfloor, however, resulting in a temperature loss that limits the passive regeneration and has to be compensated for by HC conversion over the pre-DOC in order to obtain the desired forced regeneration temperatures of about 620ºC.

Using a base metal-palladium coating to replace the Pt coating on the filter will reduce the NO_2 emission, facilitate passive regeneration and increase forced regeneration rate. At high engine temperatures, i.e. 450–550ºC, where NO_2 is limited, the base metal coating facilitates passive regeneration. During forced regeneration HC and CO are removed according to Figures 4 and 5. In order to demonstrate the advantages of the novel base metal-palladium coating, three Mercedes taxis were equipped with BMC-211 coated filters, see below.

In the third system, diesel is injected into the exhaust line just before the pre-DOC when the exhaust temperature is above 200ºC. Engine management can secure this level. Increased engine wear can be avoided by not using engine post injection.

In the fourth system, the catalyzed filter is integrated with the pre-DOC function and placed closely coupled. This means that the catalytic coating has to oxidize the engine exit HC and CO from a low temperature, i.e. 160–180ºC, and in parallel enhance passive and forced soot regeneration. For forced regeneration, the engine exhaust temperature is increased to 620ºC by post injection. The heat generated from the catalytic conversion of HC and CO adds locally where the soot is combusted and the forced filter inlet temperature can be decreased using an active catalytic coating. The temperature gradients in the filter can be higher than in the systems above and the maximum allowed soot load is lower [7].

NEDC MEASUREMENTS

A Citroën Xsara Picasso 1.6 l HDI equipped with a diesel particulate filter without a catalytic coating from the OEM according to the first system in Figure 9 was tested on a chassis dynamometer. The standard European NEDC test cycle was used.

The OEM filter was then replaced with a BMC-211 coated commercial 144 mm x 203 mm, 3.30 liter, diesel filter with 46.5 cells/cm^2 and wall thickness 0.25 mm. After 4000 km in normal city traffic, the vehicle was again tested on the chassis dynamometer. No exhaust management alarms were seen. The results are given in Table 3 together with present Euro 4 and foreseen Euro 5 vehicle regulations.

Since the Citroën is equipped with a DOC there is not much difference in the HC, CO and PM emission when using the BMC-211 coated filter as long as no forced regeneration is taking place. As expected the large difference is seen in the NO_2:NO_x ratio which is reduced from 0.357 to 0.123, a reduction that would improve the air quality in cities.

Table 3. NEDC test Citroën Picasso 1.6 l HDI with coated filter

g/km	HC	NO_x	NO_2:NO_x	CO_2	CO	PM
EURO 4		0.25			0.50	0.025
NEDC OEM	BDL*	0.229	0.357	149	0.036	0.0028
NEDC BMC-211	BDL*	0.230	**0.123**	146	0.031	0.0044
EURO 5 draft		0.18			0.50	0.005

*) Below detection limit

Three Mercedes-Benz E 280 CDI R6, 3.2 l 130 kW Euro 4, equipped with a filter system (28 cells/cm^2, 144 mm × 203 mm, wall thickness 0.25 mm) according to the second system in Figure 9 were in the same way equipped with base metal-palladium coated commercial filters. Car A was measured after 9,858 km (BMC-A1) and 13,986 km (BMC-A2). Cars B and C were measured after 25,000 km. All cars had been driving with no indication of exhaust system alarms. Chassis dynamometer NEDC tests on three Mercedes cars equipped with BMC-211 coated filter have been performed and the results are compared with the OEM filter installation on a reference car. The OEM car was measured twice. The results are collected in Figure 10. Furthermore, a measurement during forced regeneration is included for Car A (BMC-A2-REG).

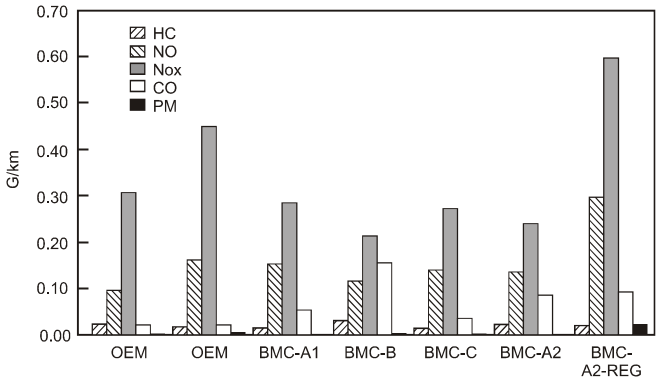

Figure 10. NEDC tests of three Mercedes E 280 CDI R6 with BMC-211 coated filter compared with one OEM vehicle

NO_x emission is lower for BMC-211 compared to OEM filter. If we look at the difference NO_x minus NO, which indicates the NO_2 emission, the BMC-211 gives a considerably lower emission than the OEM filter. HC emission is at the same level, however, CO is somewhat higher for BMC-211 compared to OEM filter but still far below the future Euro 5 limits. All emissions increase during forced regeneration.

As the NO_2 emission of the cars differs, the NO_2/NO_x ratio was calculated for the cars and depicted in Figure 11.

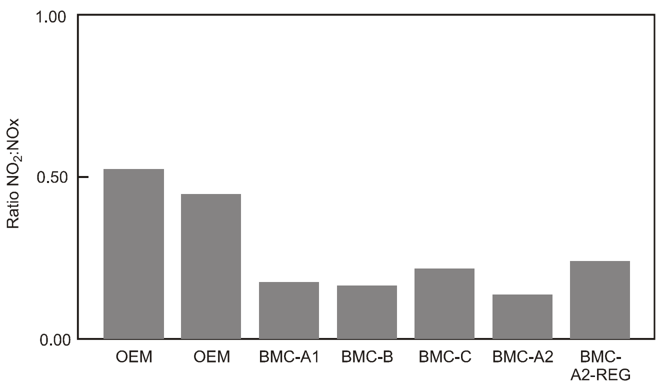

Figure 11. NO_2:NO_x ratio for OEM and BMC-211 in NEDC tests

There is a large difference in NO_2:NOx ratio between the NEDC results with BMC-211 and the OEM Pt-coated filter. The ratio is decreased from 0.5 to around 0.2. During forced regeneration, the ratio increases to 0.25, but is still 50% of the OEM level. The total NO_x reduction with BMC-211 was measured to 6%.

CONCLUSION

Pt-coated diesel filters give an NO_2 emission increase which exceeds the NO_2 limits that are to be implemented in 2010 in European cities. An alternative catalytic base metal-palladium filter coating with NO_2 reduction capabilities has been developed and tested in an engine test bench set-up. The enhancement of the new catalytic coating of passive and forced soot regeneration was demonstrated. High conversion of NO_2 and HC was demonstrated from low temperatures. The coating is thermally resistant above 900ºC. Commercial filters were installed on taxis with the two predominantly used filter regeneration systems. NEDC tests show a significant reduction of NO_2 emission for both systems.

As the novel base metal-palladium catalyst also has the ability to react NO_2 with soot or carbon monoxide at temperatures between 180ºC and 330ºC, NO_2 will be reduced both by this mechanism and by the direct reaction between soot and NO_2. The final result is that the total NO_2 emission problem is reduced.

If NO_2 originating from a pre-DOC is present in the base metal filter, a soot combustion synergy will take place with the base metal catalytic coating, and the passive regeneration temperature is extended to 250ºC–550ºC. This implies that the time between forced regenerations can be extended and fuel penalty can be lowered.

The processes and features of using a base metal-palladium coating for forced passive and forced regeneration are summarized below.

Passive soot regeneration

- Soot is combusted during normal driving conditions above 250ºC
- Soot combustion increases with increasing temperature
- Need for forced regeneration and the ensuing fuel penalty is reduced
- NO_2 from a Pt pre-DOC cannot be dosed in the right ratio to actual soot amount on filter

Role of base metal-palladium coating

- Catalyze combustion of soot in temperature range 350–550ºC
- Synergy with NO_2 from pre-DOC so temperature range is extended to 250–550ºC
- Removes NO_2 at low temperatures 170-330ºC
- Limited NO_2 formation above 330ºC
- Converts hydrocarbons from 190ºC
- Converts carbon monoxide from 190ºC

Forced soot regeneration

- Inlet filter temperature 620ºC causing fuel penalty
- Maximum soot amount and temperature in filter must be controlled
- Soot combustion with O_2 from exhaust gas
- All soot can be removed
- NO_2 and catalytic coating have limited influence on soot combustion
- Regeneration time 10–20 min.
- Insignificant NO_2 is formed on catalyst coating at this temperature due to thermodynamics and HC inhibition on the catalyst

Role of base metal-palladium coating

- Converts hydrocarbons (HC)
- Converts carbon monoxide (CO)
- The HC and CO reactions increase temperature in filter and thereby increase soot combustion rate

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

DOC – diesel oxidation catalyst

Pre-DOC – diesel oxidation catalyst placed before DPF

DPF – diesel particulate filter

CDPF – catalyzed diesel particulate filter

BPT – soot balance point temperature

OEM – original equipment manufacturer (car manu-facturer)