Advanced Emissions Aftertreatment

for Diesel Applications

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PREFACE

Looking back to the late 1980's and the activity that was taking place on ways to reduce diesel emissions, it is interesting to note several similarities to today. Particulate control was on the agenda, as well as NOx control. Although the levels were different, discussions on particulate matter centered around 0.25g/bhp-hr, and now they are centered around <0.1 g/bhp-hr. NOx discussions were about bringing levels down to <5 g/bhp-hr, whereas <2 g/bhp-hr is discussed today. As it was then, so it is now: the diesel particulate filter (DPF) is being discussed as a potential solution but with one major difference. In the late 1980s, it was to be the solution to lowering diesel emissions. Today, it is referred to as the enabling technology that will interact with engines and other technologies. And the operative word that we hear repeatedly is "enabling." All potential solutions are expected to interact with each other, and in most cases, they cannot act alone to bring the diesel emissions within the required targets.

This SAE Special Publication, Advanced Emissions Aftertreatment for Diesel Applications (SP-1543), reflects the variety of work targeting the new diesel emissions legislation levels. On many occasions, they center only on a particulate method and its potential, but they also reference other measures that need to be employed prior to the method being applicable. This collection of papers gives insight into the different technologies that could address many aspects of and concerns related to diesel emissions.

Jacques Lemaire
Rhodia Terres Rares

Dimitrios Psaras
Advanced Material Resources

Masatoshi Shimoda
Hino Motors, Ltd.

Session Organizers

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2000-01-1922

A Method for Assessing the Low Temperature Regeneration Performance of Diesel Particulate Filters and Fuel-borne Catalysts

B. Terry and P. Richards
The Associated Octel Company Limited

ABSTRACT

Fuel-borne catalysts are now an accepted means of aiding the self-regeneration of diesel particulate filters (DPFs). In the past it has been possible to assess the effect of these fuel additives by investigating the temperature at which the filter reaches a pressure drop equilibrium. Under these temperature conditions, the particulate matter is oxidised at the same rate as it is being deposited and there is thus no change in pressure drop across the filter. This technique adequately demonstrates the oxidation temperature of the carbon in the presence of the catalyst. However, it is now well known that such fuel additives also influence the low temperature oxidation of particulate bound hydrocarbons. This phenomenon is not detected by the filter equilibrium technique.

Study of the regeneration performance of filter/additive combinations at a range of steady state engine operating conditions has indicated a series of operating points that demonstrate different modes of regeneration behavior and highlight the low temperature regeneration characteristics of such systems. A seventy-hour test procedure has been developed to allow comparison of different fuel additives and different DPF technologies.

This procedure has been used to quantify the relative performance of three organo-metallic fuel additives and six DPF types. The effect of an oxidation catalyst before one of these filters has also been investigated. The work shows significant differences between fuel additives but little difference between most DPFs.

INTRODUCTION

The year 2000 heralds the next legislative measure in Europe concerning vehicle exhaust emissions. This has prompted significant effort into viable methods for reduction of particulate emissions. Further legislation standards to be implemented in 2005 together with an increased concern regarding the role of particulates on health and upon the environment are certain to ensure that particulate emission control strategies continue to be a major challenge to the automotive industry. The emissions limits for 2000 and 2005 are shown in Table 1 below.

Developments in diesel engine technology in recent years have significantly reduced carbon dioxide (CO_2), carbon monoxide (CO) and hydrocarbon (HC) emissions with some reduction in oxides of nitrogen (NOx) emissions. However, if the inherent efficiency of the diesel passenger car and commercial vehicle is to be fully appreciated, further improvements in exhaust after treatment technology and fuel technology are necessary to control particulate emissions (PM). Studies of the behavior and effectiveness of DPFs have shown this technology to be a capable solution to the problem, although the problem of securing the reliable regeneration of the filters must be resolved.

Table 1. Proposed European Union diesel exhaust emission standards for passenger cars and light commercial vehicles <1305 kg (g/km)

Year	2000	2005
PM	0.05	0.025
CO	0.64	0.50
NOx + HC	0.56	0.30
NOx	0.50	0.25

A number of particulate filter systems have been extensively studied and reported upon (1-4). The main functions of the DPF system can be summarised as follows:

- to filter and trap the mainly carbonaceous particles to eliminate visible black smoke and reduce the mass of emitted particulate
- to overcome the accumulation of soot on the filtering surface by ignition and oxidation of the particulates, either continuously or at regular intervals, to minimise the increase in exhaust back-pressure, which tends to reduce the engine's efficiency, and to increase fuel consumption.

The ignition temperature of carbon particulates is around 500°C to 600°C, vastly above the 200°C exhaust temperatures of average traffic speeds under modern urban driving conditions. Various operations have been tried to promote oxidation of the trapped soot, many of which require some form of external device (5-9). However, for any particulate control strategy to be attractive to manufacturers, it must be reliable, effective, robust and low-cost. In addition, the internal temperatures reached during regeneration must not exceed the safe thermal operating temperature of the DPF. The author's experience has been that excessive temperatures reached during uncontrolled regenerations limit the life of the device or cause failure.

One solution implemented by the authors has demonstrated selected fuel-borne catalysts can be effective in inhibiting the formation of, or in aiding the oxidation of, particulates to promote self-regeneration of DPFs. Fuel-borne catalysts are now an accepted means of aiding the self-regeneration of DPFs (10-15) and work undertaken by others has assessed the effect of fuel additives by investigating the temperature at which the DPF reaches a pressure drop equilibrium. Under the temperature conditions investigated the particulate matter is oxidised at the same rate as it is being deposited and there is thus no change in pressure drop across the filter. This technique adequately demonstrates the oxidation temperature of the carbon in the presence of the catalyst and shows the fuel-borne catalyst to effectively regenerate DPFs at high engine loads. However, it is now well known that such fuel additives also influence the low temperature oxidation of particulate bound hydrocarbons. This phenomenon is not detected by the filter equilibrium technique.

The regeneration performance of DPF/additive combinations over steady state engine operation has previously indicated operating conditions that demonstrate different modes of regeneration behavior. Significantly, the low temperature regeneration characteristics of such systems have been highlighted. A seventy-hour test procedure has been developed to allow comparison of different fuel additives and different DPF technologies.

This procedure has been used to quantify the relative performance of three different organo-metallic fuel additives and five DPF types over a range of critical engine operating conditions. The effect of an oxidation catalyst before one of these filters has also been investigated.

TEST ENGINE, EQUIPMENT AND FUEL

The work was undertaken using a Peugeot XUD-9A engine mounted on a pallet arrangement and equipped with appropriate heat exchangers, electrical connections and connectors for instrumentation signals. This pallet arrangement was connected to the engine test bench. The engine dynamometer was a Froude AG150 eddy current machine controlled by the CP Engineering Cadet system. Engine operating temperatures were controlled automatically by suitable 3-term controllers integrated into the secondary coolant system supplies. The test bench was controlled and data logged using a CP Engineering Cadet system.

The test engine was of the indirect injection (IDI) type, employing a Ricardo Comet type pre-chamber design. The engine design was a four cylinder, in-line with a single overhead camshaft operating two valves per cylinder. The total swept volume of the engine was 1905 cm^3. The engine was naturally aspirated with a 23.5 : 1 compression ratio and was fitted with a Roto-Diesel fuel pump and Bosch pintle type fuel injectors.

The engine exhaust system was modified to allow ready interchange of a center section which could incorporate a selection of DPFs and an oxidation catalyst where necessary.

Two types of silicon carbide (SiC) DPF, one Cordierite and three Deep Bed DPFs were assessed. In addition, an oxidation catalyst was also subjected to limited testing in conjunction with one of the SiC DPFs.

The non-additised base fuel used throughout this study was an EN 590 specification fuel. An analysis of the fuel is given in Appendix 1. Three different fuel-borne catalysts were tested. The metals present in the three additives were cerium, iron and a combination of iron and strontium in the ratio of 4:1. All the additives were added to the base fuel to give a total treat rate of 20 ppm of metal.

TEST METHOD

Extensive previous work had led to the development of a vehicle test procedure to allow performance screening for candidate fuel additives and different DPF technologies. Initial investigations on an engine test bench had identified two test conditions which gave contrasting DPF regeneration performance.

Subsequent test work was undertaken at test points taken from a matrix of nine engine speeds and twelve engine torques which included these conditions (16). The test matrix for this programme of work, using a passive SiC DPF in conjunction with a sodium/strontium additive is shown Table 2. For this work the engine was run for a number of hours at the appropriate steady state condition and the DPF was allowed to accumulate soot.

To protect the DPF from thermal damage, resulting from excessive soot burnout, an arbitrary exhaust back pressure limit was set for each of the operating conditions. If this limit was reached the engine duty was increased to raise the exhaust gas temperature to the point where the trapped soot would oxidise. These conditions are indicated by an × in Table 2. If however, the soot spontaneously oxidised during normal steady state operation then no further action was required. These points are indicated by the ✓ in Table 2. A blank cell in the table indicates that this particular condition was not tested.

Table 2. Silicon Carbide DPF test matrix: Na/Sr additive

		Engine speed (rev/min)								
		1260	1550	1840	2130	2420	2710	3000	3580	4160
Engine Torque (Nm)	5									
	10									
	15									
	20		×		×					
	25	✓	×	×						
	30	✓	✓	×	✓	✓		×		
	35	✓	✓		✓					
	45	×		×		×		✓		
	60	✓		✓		×		×		
	75			×		×				×
	100			×		×		✓	✓	
	full rack			×		✓		✓	✓	

This work identified a region of low duty operation would work well as indicated by a ✓ in Table 2. A region of high duty operation was also identified where the system worked well. This is also indicated by a ✓. The table also shows a region of very low duty where the system did not work, indicated by an ×.

Further to this, work was conducted on a Cordierite DPF in combination with an iron based additive (17). Table 3 shows the conditions used in this test matrix. Again a blank cell indicates that testing was not performed at that condition. It can be seen from Table 3 that this work also showed a region of low duty operation where the system would work well (✓) and a region of high duty operation where the system also worked well. As in the previous work displayed in Table 2, there appeared to be a region in between, though in this case much smaller, where the system appeared not to work within the arbitrary limits imposed. Again this is indicated by an × in the table.

From the work above, it was clear that simply achieving a sufficiently high exhaust gas temperature did not guarantee DPF regeneration. From Table 2, for example, at 1840 rev/min at 75 Nm, stochastic regeneration does not occur. However, at 1840 rev/min and 60 Nm where one would expect exhaust gas temperature to be lower than at 1840 rev/min and 75 Nm, regeneration does occur. Similarly, Table 3 displays a condition at 3000 rev/min and 30 Nm where stochastic regeneration does not occur. At 1840 rev/min and 30 Nm, where we assume the exhaust gas temperature will be lower, regeneration does occur.

Table 3: Cordierite DPF test matrix: Fe additive

		Engine speed (rev/min)								
		1260	1550	1840	2130	2420	2710	3000	3580	4160
Engine Torque (Nm)	5	✓								
	10	✓	✓							
	15	✓	✓							
	20	✓	✓	✓	×					
	25									
	30	✓	✓	✓	×	×		×		
	35									
	45				×					
	60			✓				✓		
	75		✓			✓		✓	✓	
	100			✓		✓		✓	✓	
	full rack									

Clearly, stochastic regeneration of the DPF system should be considered as having a number of distinct modes of operation. These may be dependent on a number of factors including additive composition, the composition of the soot particles, the exhaust oxides of nitrogen and the oxygen content.

From these investigations, a series of operating conditions were chosen that were considered to be critical for low temperature regeneration. The 1260 rev/min point was chosen as this corresponded to the lowest operating temperature. A typical pressure and temperature trace for this operating condition is shown as Figure 1.

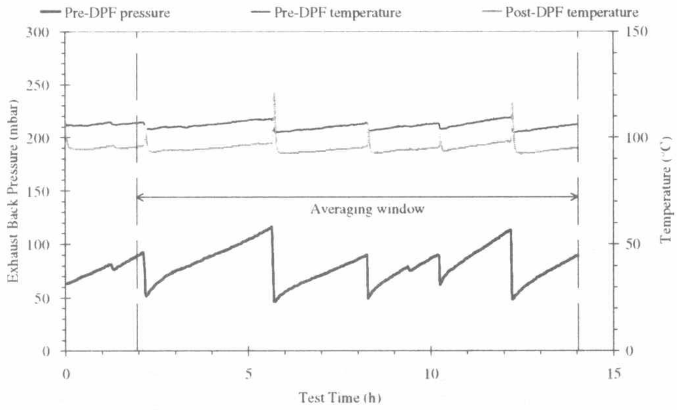

Figure 1: Typical temperature and pressure trace at 1260 rev/min, 5 Nm with a SiC DPF

The averaging window, seen in the figure above, indicates the section of the trace that has been used to determine average exhaust back pressure and temperatures at this operating condition. The window is set such that the exhaust pressure at the start and finish of the window is equal, thus eliminating any warm up effects. The mean exhaust back pressure is then used as the criterion for assessing the system performance.

The lower the mean exhaust back pressure, the better the system performance.

Figure 1 also clearly demonstrates the non-equilibrium characteristics of low temperature self-regeneration. The exhaust back pressure increases steadily, as soot accumulates, until it is approximately double its original value before a regeneration takes place. Following the regeneration the back pressure normally returns to that of the non-loaded DPF, i.e. a complete regeneration. The mean pre-DPF exhaust gas temperature for the test shown in Figure 1 is only 105ºC. Also due to the soot that accumulates there are noticeable exotherms occurring. The range of post-DPF gas temperature is 92ºC to 122ºC which is more than three times the variation in pre-DPF temperature of 102ºC to 110ºC.

The results shown in Tables 2 and 3 indicate that at 1550 rev/min and light load there was a difference in performance between the two systems. Two operating conditions were thus chosen, at this speed, to straddle what was considered to be a critical boundary.

Two different speeds were chosen at 30 Nm, again as it was thought that this straddled a boundary of change in operating characteristic. A typical trace from one of these conditions, 2710 rev/min at 30 Nm, is shown in Figure 2 below.

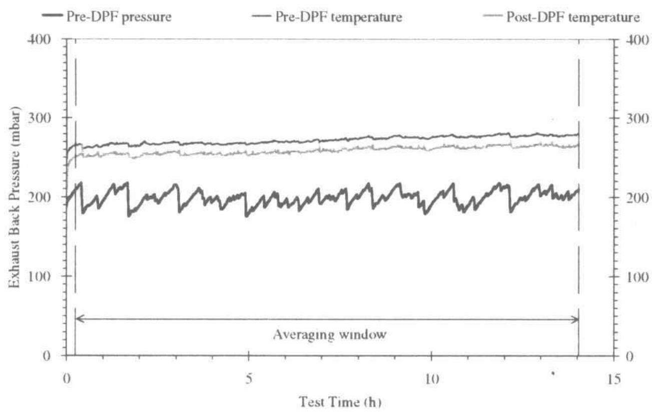

Figure 2. Typical temperature and pressure trace at 2710 rev/min, 30 Nm with a SiC DPF

This figure clearly demonstrates a different regeneration characteristic. Soot is accumulating, and hence back pressure increasing, at a similar rate, however regenerations are occurring at far more frequent intervals. This condition is thus more akin to the equilibrium condition but again the temperatures are much lower than would be expected for the catalysed oxidation of carbon.

The mean pre-DPF temperature for Figure 2 is only 272ºC. As less soot is accumulated prior to regeneration the exotherm produced is smaller. The range of post-DPF temperatures for this test was 249ºC to 273ºC, only slightly more than the variation in pre-DPF temperature of 261ºC to 281ºC.

A set of five test points was thus derived for future testing; Table 4 shows the portion of the test matrix from which the test points have been chosen and the five test points are marked with a *.

Table 4: Test matrix

		Engine Speed (rev/min)			
		1260	1550	2710	3000
Engine Torque (Nm)	5	*			
	10		*		
	20		*		
	30			*	*

For each of these test conditions the engine was operated for 14 hours. The arbitrary exhaust back pressure limit was set to 300 mbar for each of the operating conditions. The test protocol thus consisted of the following;

- start the engine, allowing a minute for the engine fluids to begin to warm up
- run for a total of 70 hours at the steady state operating conditions
- run the engine at the high duty operating condition to produce a forced regeneration in order to secure soot burnout prior to the next test.

Tests were run with the five operating conditions in two alternate test sequences. The first sequence used the operating conditions in the following order 1260/5, 2710/30, 1551/20, 3000/30 and 1550/10. The second sequence used the operating conditions in the alternate order of 3000/30, 1551/10, 1260/5, 2710/30 and 1551/20. This was done to indicate whether there was any influence, on regeneration, performance, from the previous operating condition.

In general there was no systematic difference in the result dependent upon the order of testing with the exception of the 1260 rev/min, 5 Nm test condition. If the 1260 rev/min, 5 Nm condition was first in the sequence then the one minute warm-up time was insufficient to ensure the engine was up to operating temperature by the start of the test. This then influenced the results, because at such a low duty condition the warm-up time became significant compared with the overall test time. If the 3000 rev/min, 30 Nm condition was tested first then the warm up time was not significant.

COMPARISON OF DPFS

Three different wall flow DPFs were assessed using the technique described above. The first unit was the familiar cordierite unit of approximately 2.5 litres volume.

The other two units were constructed of silicon carbide and were of the same volume. The two SiC DPFs differed in their cell densities and cell wall thickness. All of these DPFs were tested using the iron/strontium fuel additive with a total metal treat rate of 20 ppm. Each DPF was tested at least twice; the average mean exhaust back pressure for each of these tests is presented in Figure 3.

From Figure 3 we can see that the cordierite DPF gives slightly lower engine back pressure than either of the two SiC DPFs at all the operating conditions tested. At the low load conditions of 1260 rev/min, 5 Nm torque and 1550 rev/min, 10 Nm torque, this difference is more significant than at the higher speed and torque conditions.

It has been suggested that the lower thermal conductivity of the cordierite monolith would reduce heat loss from the particulate, thus yielding higher particulate temperatures and improved regeneration characteristics. Hence the lower mean engine back pressure values that are exhibited here. However, at higher power conditions, the exhaust gas flow rate, and hence energy input to the trapped particulate, is higher. The difference in thermal conductivity of the substrate thus becomes less significant.

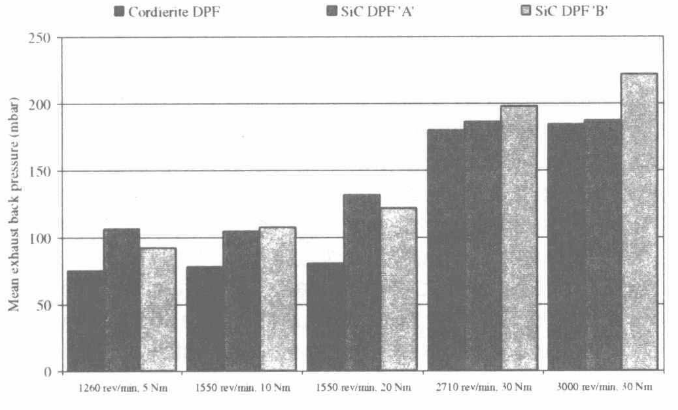

Figure 3. Comparison of Cordierite and two SiC DPFs

Three deep bed filters were also tested. Filters 'C' and 'E' were of the same volume but with different fibre packing densities whilst filter 'D' was of a greater volume. Again all three filters were tested using the iron/strontium additive. The average mean exhaust back pressure for the different deep bed filters is presented in Figure 4.

The data presented in Figure 4 show a consistent benefit from the use of Deep Bed DPF 'C' at all of the conditions tested with the exception of the very low load condition of 1260 rev/min, 5 Nm torque. In this case, the mean engine back pressure is comparable with DPF 'D'. In contrast to this, the DPF 'E' consistently shows the poorest performance in terms of mean engine back pressure. In particular, at 1550 rev/min, 10 Nm torque and 2710 rev/min, 30 Nm torque the mean back pressure is over twice that of DPF 'C' under the same engine conditions. Overall, the performance of DPF 'D' is somewhere between DPF 'C' and 'E' although, in three out of the five operating conditions, the engine exhaust back pressure is closer to that of DPF 'C'.

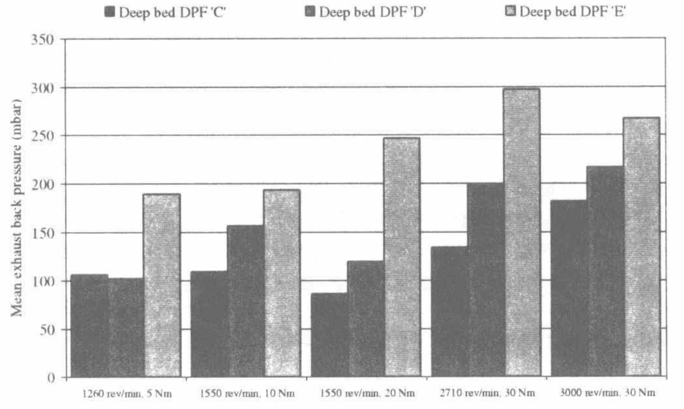

Figure 4. Comparison of Deep Bed DPFs

As was discussed earlier, it is thought that the low temperature burn-out that is being observed in this work is due to the fuel borne catalyst acting upon the unburned hydrocarbon bound up within the particulate. To comply with future emissions legislation it is almost certain that an oxidation catalyst will have to be fitted to control CO and HC emissions. To ensure optimum efficiency from this catalyst, it would have to be fitted as close as possible to the engine. The question then arises as to whether the inclusion of an oxidation catalyst upstream of the DPF would significantly impair low temperature regeneration performance.

To investigate this problem, a test was run with an oxidation catalyst directly upstream of the SiC DPF 'B'. The mean exhaust back pressure from the test with the catalyst is presented in Figure 5 along with the corresponding data for the SiC DPF alone.

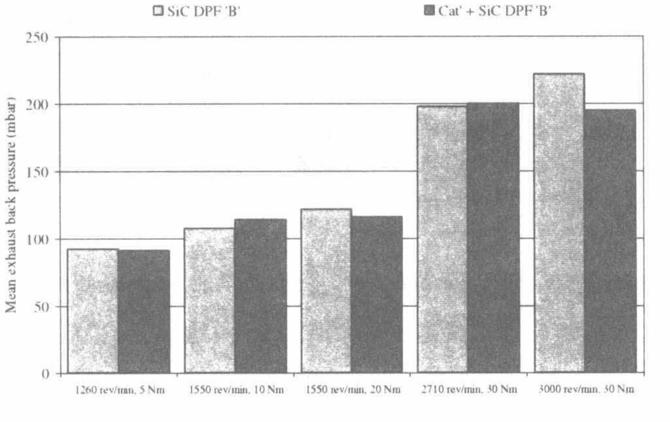

Figure 5. Comparison of SiC DPF 'B' with and without an oxidation catalyst

From Figure 5 it is clear that the catalyst is not significantly impairing the regeneration performance of the DPF. At the three lower speed operating conditions, consideration of the temperatures involved make the reason for this apparent. The temperature of the exhaust gas passing through the catalyst and DPF is still below 200ºC and there is little activity over the oxidation catalyst, CO conversion efficiency is below 5% and HC conversion efficiency is below 50%. At the two higher speed and load points the oxidation catalyst efficiency is high for gaseous emissions, CO conversion efficiency is 99% and HC conversion efficiency is about 80%, however the catalyst does not apparently have a significant effect on the particulate bound hydrocarbon. The slight increase in temperature, due to the activity across the catalyst, at the high speed condition may in fact aid the regeneration of the DPF. A fuller discussion of the emissions performance of the DPF catalyst combination will appear in a later paper.

COMPARISON OF ADDITIVES

To determine whether running the engine at these conditions would discriminate between different fuel-borne catalysts, tests were run using an iron and an iron/strontium fuel additive. Both additives were used at the appropriate treat rate to give a total of 20 ppm of metal in the fuel. The additives were both tested in the same SiC DPF.

The results of these tests are presented in Figure 6. Although the data at the lightest load condition were lost from one of these tests, the results clearly show a benefit from the additive containing the combination of iron and strontium when compared with the additive containing only iron. The benefit is between 18% and 32% reduction in the mean exhaust back pressure that would be experienced with iron alone.

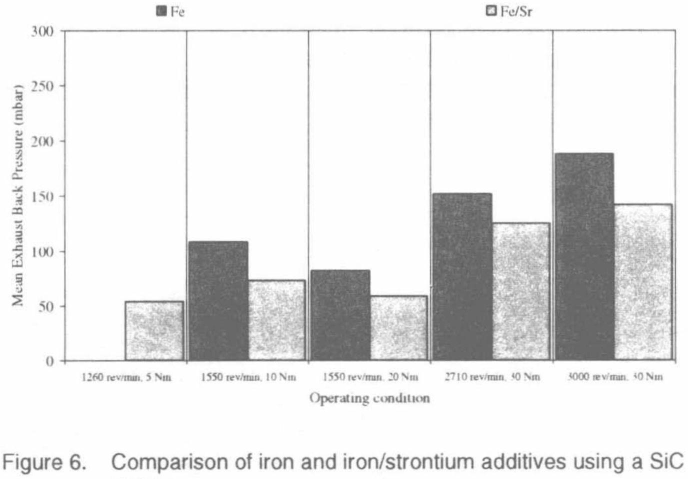

Figure 6. Comparison of iron and iron/strontium additives using a SiC DPF

To further validate the efficacy of the method, three different additive technologies were tested in a cordierite DPF. The metal ions in the three different chemistries were; cerium, iron and a combination of iron and strontium. All three additives were again treated at a dose rate corresponding to 20 ppm of metal. To ensure that there was no influence on performance from residual additive ash, each additive was tested using a dedicated DPF. Three cordierite DPFs were used for this work. Each additive was tested at least twice to determine the mean exhaust back pressure. The results of this testing are shown in Figure 7.

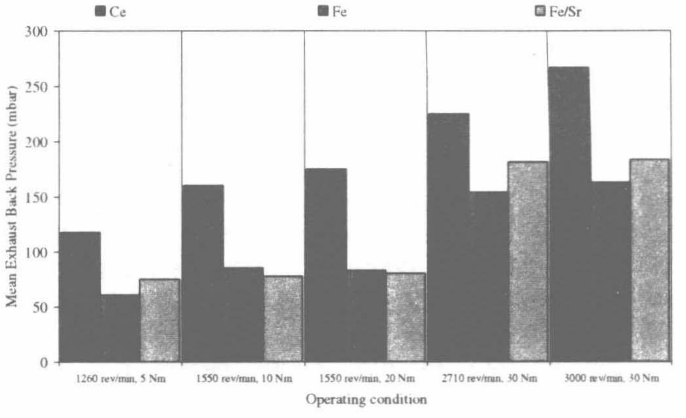

Figure 7. Mean exhaust back pressure results obtained from three different additives using a Cordierite DPF

Figure 7 clearly demonstrates that the cerium additive gives greater exhaust back pressure results compared with the other two additives at the same conditions. One possible explanation for this is that the additives were treated to give equal metal mass treat rates. Due to the differences in the atomic weight of iron and cerium, the molar concentration of iron is far greater than that of cerium. This would then lead to a greater number of metallic particles in the particulate which may account for the increased activity.

The difference in mean exhaust back pressure between the iron and iron/strontium additised fuels is much smaller. At three of the five conditions examined, the iron based additive gives a slightly lower mean exhaust back pressure, contrary to the results obtain in the SiC DPF. However, when the data are analysed statistically, these differences become less significant. Figure 8 depicts the data plus or minus two standard deviations from the average value of mean exhaust back pressure.

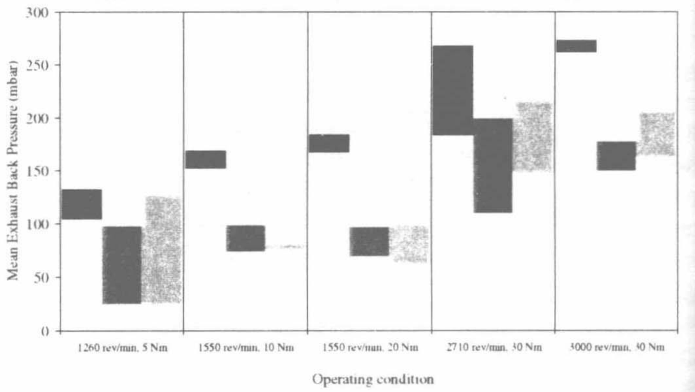

Figure 8. Mean plus and minus two standard deviations with three additives using a SiC DPF

Where the respective bars do not overlap the differences are considered statistically significant. Figure 8 shows a relatively large spread between the iron and iron/strontium blends at the five test conditions, indicating no statistically significant performance advantage between the two.

CONCLUSIONS

From the work reported here the following conclusions have been drawn:

- a seventy hour bed engine test procedure has been developed which can be used to assess the low temperature regeneration performance of different DPFs in conjunction with fuel-borne catalysts
- the test procedure adequately covers the different modes of regeneration performance encountered at these low temperatures
- the test procedure demonstrates that the fuel-borne organo-metallic additives tested are effective in promoting the stochastic regeneration of the DPF system at these low temperatures
- work performed using this test method demonstrates significant differences between the low temperature regeneration performance of the different fuel-borne additives tested
- the work performed shows that alternative DPF technologies can achieve similar levels of performance, however variations in the configuration of a given technology can produce different performance levels
- limited testing, by this method, also showed that there is no significant loss of low temperature regeneration performance through the use of an oxidation catalyst upstream of the DPF. This is an important result for future after-treatment applications given the increasing use of oxidation catalysts in current and future passenger cars.

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APPENDIX 1

Fuel Analysis

Density, kg/litre @ 15°C	0.8320
Viscosity, cSt @ 40°C	2.727
Cloud point, °C	-4
CFPP, °C	-17
Pour point, °C	-27
Sulphur content ,mg/kg	323
Distillation,	
IBP @ °C	163.5
5% vol @ °C	193.0
10% vol @ °C	205.0
20% vol @ °C	224.5
30% vol @ °C	244.0
40% vol @ °C	259.5
50% vol. @ °C	274.0
65% vol. @ °C	293.5
70% vol @ °C	300.0
85% vol @ °C	325.5
90% vol @ °C	336.5
95% vol @ °C	350.5
FBP @ °C	361.0
% vol recovery	98.6
% vol residue	1.3
% vol loss	0.1
FIA analysis	
% vol saturates	76.4
% vol olefins	1.6
% vol aromatics	22.0
Cetane number CN	52.9
Calculated cetane index CNI	54.5
Flash point, °C	62.0
CNI content, % v/v	0.000

2000-01-1923

Particulate Traps for Construction Machines Properties and Field Experience

J. Czerwinski
AFHB

M. Wyse
BUWAL

F. Jaussi
Liebherr

A. Mayer
TTM

1. ABSTRACT

Occupational Health Authorities in Germany and Switzerland require the use of particulate traps (PT) on construction machines used in underground and in tunneling since 1994. Swiss EPA has extended this requirement 1998 to all construction sites which are in or close to cities. During the VERT*)-project, [1, 2, 3, 4, 5]**), traps systems were evaluated for this purpose and only those providing efficiencies over 95% for ultrafine particles < 200 nm have received official recommendation. 10 trap-systems are very popular now for these application, most of them for retrofitting existing engines. Efficiency data will be given as well as experience during a 2-years authority-controlled field test.

LIEBHERR, producing their own Diesel engines in Switzerland and construction machines in Germany is the first company worldwide supplying particulate traps as OEM-feature (Original Equipment Manufacturing) on customers request. LIEBHERR has decided to use the passively regenerating OBERLAND-system with OCTEL iron based fuel regeneration. An information about the experiences with this particulate trap system will be given.

*) abbreviations see chap. 10
**) references see chap. 9

2. INTRODUCTION

Extensive Swiss tunnel-projects prompted the joint project VERT to evaluate pertinent measures for more stringent limits for Diesel particulate emissions. A limit of 0.2 mg/m^3 concentration in respiratory air was specified for occupational health reasons.

The results of the 4-year investigations, of construction site engines on test rigs and in the field, are clear: particulate trap technology is the only acceptable choice among all available measures. Fortunately, traps proved to be an extremely efficient method to curtail the finest particles. Several systems demonstrated a filtration rate of more than 99% for ultra-fine particulates. Specific development may further improve the filtration rate.

A two-year field test, with subsequent trap inspected, confirmed the results concerning the filtration characteristics of ultra-fine particles.

Particulate traps represent the best available technology (BAT). Traps must therefore be employed to curtail the particulate emissions, which are demanded by law to be minimized.

The Swiss EPA established a recommendation list of proved particulate traps, which have been investigated either during the VERT-test, or in the VERT-suitability test and fulfill the quality requirements.

Also the equipment and regulations for the field control of PT-systems, as well as the periodic control of all pollutant emissions of the building machinery have been fixed.

3. VERT PROJECT

VERT is a European joint project targeted at reducing the exhaust gas emissions, of existing Diesel engines, using commercial methods [6, 7, 8]. Thus the recently tightened imission criteria at tunnel sites can be surely fulfilled. The workmen's compensation agencies SUVA (Switzerland), AUVA (Austria) and TBG (Germany) initiated the project in 1993 together with the Swiss Federal Environmental Protection Agency BUWAL.

A significant group of industrial partners participated from the beginning in the project. They supplied their products, technical advice and financial resources.

- Engine manufacturers:
  LIEBHERR, CATERPILLAR, DEUTZ
- Exhaust gas after-treatment:
  HUSS, UNIKAT, ECS, 3M, DEUTZ, BUCK, HUG, SHW, HJS, GILLET
- Fuels and fuel additives:
  RHODIA, PLUTO, LUBRIZOL, DEA, GREENERGY
- Field measurement instruments:
  TESTO, MRU, RBR, AVL, VLT

The investigations benefited from the many Swiss research institutes. They have been actively investigating for decades the emission of ultra-fine particulates from Diesel combustion. These institutes participated in the project as laboratory partners:

- AFHB: Engine tests
- ETHZ: Nano-particulate analysis
- EAM: Nano-particulate analysis, calibration
- EMPA: Analysis of dioxins, trace metals, VOC
- PSI: Trace analysis
- Suva: Coulometry, field measurements

VERT Objectives

The most important objectives of the VERT-project can be summarized as follows:

- to diminish the emissions at the source (with special regard to the particulate matter and nano-particles)
- to define the new limit values of emissions
- to find the methods and apparatus to control the machines in the field
- to confirm the feasibility of the particulate traps (PT) and regeneration systems in the field tests
- to give support to the users by introducing the PT-systems

VERT Field Test

A field test with 10 engines was run between October 1995 and June 1997. 4 different filter media and 4 regeneration systems were tested. Over 23000 hours were accumulated, [3, 9].

Following tables show: the engines, particle filters, filter materials and regeneration systems, which were utilized during the field test.

Engine Type	Manu-facturer	Regeneration	Time of use [h]	Symbol
Liebherr				
D904T	SHW (HSJ)	Eolys (Ce) satacen (Fe)	1846	LIB1/SHW
D904T	BUCK	Catalytic coating	1270	LIB2/BUCK
D914TI	ECS	Lubrizol (Cu)	2061	LIB3/ECS
D916T	Deutz	full flow Diesel burner	1705	LIB4/DSI
Caterpillar				
3306TA	SHW	satacen (Fe)	1534	CAT1/SHW
3306T	Deutz	full flow Diesel burner	1724	CAT2/DSI
3116T	BUCK	satacen (Fe)	250	CAT3/BUCK
3118	UNIKAT	electrical off-line	6933	CAT4/UNIKAT
3406T	UNIKAT	electrical off-line	2775	CAT5/UNIKAT
3116T	HUG	catalytic coating	1707	CAT6/HUG

(shaded) ... not analyzed after the field test

Table 1: Engines and particle filters in the VERT field test