International Journal of Automotive Technology, Vol. 3, No. 1, pp. 1–8 (2002)

1229–9138/2002/007–01

EFFECTIVE PARTICULATES REDUCTION IN DIESEL ENGINES THROUGH THE USE OF FUEL CATALYSED PARTICULATE FILTERS

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(Received 27 February 2001)

ABSTRACT–There is increasing world-wide interest in diesel particulate filters (DPF) because of their proven effectiveness in reducing exhaust smoke and particulate emissions. Fine particulates have been linked to human health. DPF use requires a means to secure the burn-out of the accumulated soot, a process called regeneration. If this is not achieved, the engine cannot continue to operate. A number of techniques are available, but most are complex, expensive or have a high electrical demand. The use of fuel additives to catalyse soot burn-out potentially solves the problem of securing regeneration reliably and at low cost. Work on organo-metallic fuel additives has shown that certain metals combine to give exceptional regeneration performance. Best performance was achieved with a combination of iron and strontium based compounds. Tests were carried out on a bed engine and on road vehicles, which demonstrated effective and reliable regeneration from a low dose fuel additive, using a single passive DPF. No control valves, flow diverters, heaters or other devices were employed to assist regeneration. Independent particle size measurements showed that there were no harmful side effects from the use of the iron-strontium fuel additive.

KEY WORDS : Diesel, Particulate, Exhaust, Emissions, Filter, Trap, Fuel additive

1. INTRODUCTION

Investigation into diesel particulate filters (DPF) or traps has a history of more than 20 years, with many papers published on the subject. The literature shows that DPFs are very effective in reducing particulate emissions, having a trapping efficiency of over 90%. However the need to achieve reliable regeneration is essential, as without it the engine cannot continue to operate (Johnson *et al.*, 1994). Various methods to assist regeneration have been tried, including electrical heaters, fuel burners, catalytic coatings and the use of fuel soluble additives. The use of electrical heating and fuel burners tends to be both complex and expensive, while catalytic coatings can suffer from soot covering catalytic surfaces, unless operating regimes are consistently favourable for regeneration. The advantage of using a fuel soluble additive as a regeneration catalyst, is that the additive is intimately combined with the soot during the combustion process. As a result, the problem of filter clogging can be eliminated.

The use of DPFs, with fuel additives to promote filter regeneration, was recognised as a simple, reliable and cost effective solution to the problem of poor air quality in tunnelling applications in Germany, Austria and Switzerland (Mayer *et al.* 1999). Following the VERT programme, the German environmental body, the UBA, now accepts the combination of approved fuel additives containing metals, in combination with effective DPF units (Umweltbundesamt, 1997).

Associated Octel has been developing DPF fuel additives for nearly 10 years, and now has UBA accepted additive chemistry for use with DPFs for effective particulate reduction. Work leading up to this position has included bed engine and vehicle testing of DPFs, to establish regeneration additive performance, combined with no-harm studies. No-harm studies have covered particle size measurements, and the effect on both regulated and unregulated emissions. Data have been published in several conference papers (Dementhon *et al.*, 1995; Vincent *et al.*, 1998; Richards *et al.*, 1999; Vincent *et al.*, 1999; Richards *et al.*, 2000).

2. MATERIALS AND METHODS

2.1. Bed Engine Testing

Extensive bed engine testing was carried out using a 4 cylinder 1.9 litre indirect injection (IDI) naturally aspirated diesel engine. This engine was selected because of its widespread use in passenger cars and light commer-

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Table 1. Details of engines used for test work.

Engine code	A	B	C	D
Engine configuration	Naturally aspirated indirect injection	Turbocharged direct injection	Naturally aspirated direct injection	Naturally aspirated direct injection
Engine type	XUD 9A	IZ	Phaser 90	6B 5.9
Bore (mm)	83.0	79.5	100	102
Stroke (mm)	88.0	95.5	127	120
Displacement (cm^3)	1905	1896	3990	5886
Compression ratio	23.0 : 1	19.5 : 1	16.5 : 1	17 : 1
Maximum power (kW)	52	66	60	86
Maximum power speed (rpm)	4600	4000	2800	2500
Maximum torque (Nm)	120	202	270	380
Maximum torque speed (rpm)	2000	1900	1400	1500

cial vehicles in Europe. Details of the engine are given in Table 1. The bed engine used is coded type "A".

A screening test protocol was established to quantify the regeneration performance of various additive chemistries, as reported elsewhere (Vincent *et al.*, 1998; Richards *et al.*, 1999). It is well known that high speed, high load conditions produce more particulate matter and soot than low speed operation. However, high speed and load operation does not produce the most demanding regeneration condition, since exhaust temperatures are also higher. In fact it is possible to achieve an equilibrium exhaust temperature at high speed and load conditions, where particulate matter burns inside the soot trap at the same rate as it is deposited. Constant temperatures and pressures are therefore evident in the trap (Vincent *et al.*, 1999). At low load conditions, however, exhaust temperatures are much lower, and back pressure is much more likely to increase progressively over time as soot accumulates within the trap. Regeneration only occurs infrequently, when sufficient soot has accumulated to permit it. It is these relatively low load conditions which in fact constitute the most severe test of regeneration additive performance, and were chosen to check performance. Five standardised speed/load conditions, selected as representing severe operating conditions, form the basis of the constant speed test protocol. These five speed/load conditions, at which regeneration has been shown to be marginal, were as follows: 1260 rev/min, 5 Nm, 1550 rev/min, 10 Nm, 1550 rev/min, 20 Nm, 2710 rev/min, 30 Nm, 3000 rev/min, 30 Nm. For all the additive tests carried out, an additive treat rate delivering 20 mg/kg metal was used.

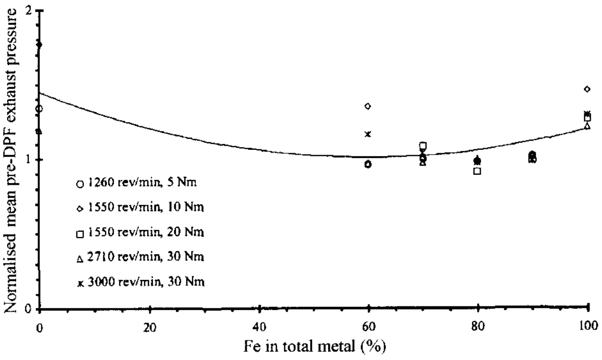

Figure 1. Effect of Fe/Sr ratio on normalised mean exhaust pressure (including results at 0% Fe).

The parameter used to compare regeneration performance for each ratio of the metals, was mean exhaust back pressure (MEBP) plus twice the standard deviation (SD). This value was calculated from increase in back pressure as a result of soot accumulation prior to the regeneration event. Frequent regeneration events resulted in small increases in back pressure, with correspondingly low values of MEBP + 2SD. Conversely, infrequent regeneration events, leading to large increases in back pressure gave a higher value of MEBP + 2SD. To present a clearer comparison of results achieved at different engine operating conditions, values of MEBP + 2SD have been normalised relative to the average of the results obtained for additive preparations containing 70%, 80% and 90% iron. These results are given in Figure 1, which shows the effect of changing the strontium to iron ratio on regeneration performance, for the five speed/load conditions tested (Vincent *et al.*, 1999). Best performance was obtained at an iron to strontium ratio of 4 : 1. This ratio was then used to evaluate regeneration performance with the bed engine over a wide range of engine operating conditions.

Figure 2 shows results obtained at 1260 rev/min,

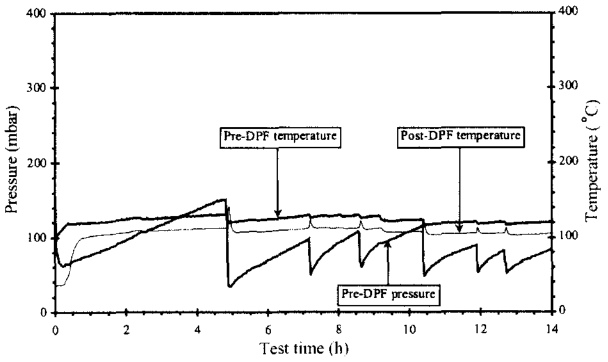

Figure 2. Regeneration performance with iron/strontium, SiC DPF: 1260 rev/min, 5 Nm.

5 Nm, over a 14 hour operating period (Vincent *et al.*, 1999). A silicon carbide (SiC) DPF was employed for the tests. Despite the very low engine speed and load, the additive catalysed regeneration at exhaust temperatures of about 120°C. This would have been impossible without the fuel additive.

Figure 3 shows results obtained at 3000 rev/min, 30 Nm, over the same 14 hour period (Vincent *et al.*, 1999). Despite the high speed/low load operating condition, which produced very dry soot, and represented unfavourable conditions for regeneration, the optimum combination of strontium and iron in this additive formulation catalysed reliable and frequent regeneration.

2.2. Vehicle Testing – Cars

Three diesel passenger cars were tested with different DPF technologies, each using the iron/strontium additive at a treat rate giving 20 mg/kg metal in the fuel. Tests were carried out on one VW Golf and two Peugeot 306 passenger cars. The Peugeot 306 cars were equipped with engines of type "A" in Table 1. The VW Golf used engine type "B" in Table 1. One Peugeot 306 car was fitted with a Cordierite ceramic DPF, and the other with a DPF using ceramic fibre technology. The VW Golf was fitted with a silicon carbide (SiC) filter. All the cars were equipped with instrumentation to monitor temperatures upstream and downstream of the DPF unit, and the pre-DPF pressure. This parameter gave effective exhaust back pressure as seen by the engine. The cars were also equipped with data loggers to record pressure and temperatures, and engine speed. Limitation on data logger channels prevented the measurement of pressure downstream of the DPF.

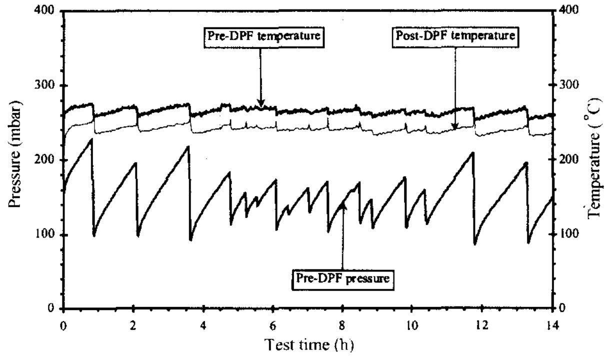

Figure 3. Regeneration performance with iron/strontium, SiC: 3000 rev/min, 30 Nm.

The Peugeot cars were operated for 5000 km each to assess regeneration performance with the different DPF types, while the VW Golf was operated for 50,000 km. This trial was carried out not only to assess regeneration performance, but also to gain experience of operation over a much longer period. Emissions measurements were made at the start of the test, and also at 10,000, 25,000 and 50,000 km on the VW Golf. The emissions data gave valuable information about DPF performance, and also established its resistance to thermal damage from repeated regeneration events. Samples of crankcase lubricating oil were taken at intervals of approximately 5000 km. These samples were used to assess engine wear characteristics.

2.2.1. Peugeot 306 – cordierite DPF test data:

Figure 4 shows an example of a regeneration event in the Cordierite DPF, while the vehicle was being driven in an outer urban environment (Richards *et al.*, 2000).

Figure 4 shows a clear exotherm resulting from soot burn-out, at about the same time as exhaust back pressure falls. Pre-DPF pressure reduces after the soot accumulated in the filter has burnt. The regeneration event only lasts about one minute; rapid soot combustion is another characteristic of the use of a metallic fuel catalyst. Immediately prior to regeneration, pre-DPF temperature

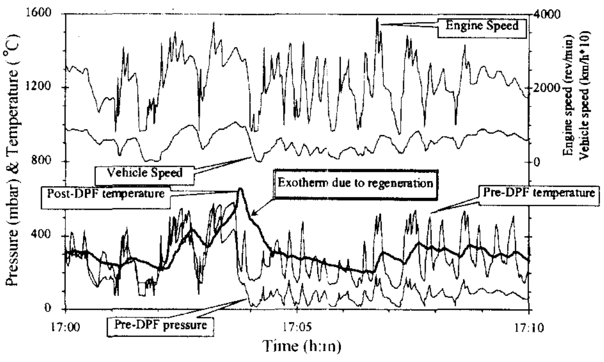

Figure 4. Regeneration with Cordierite DPF.

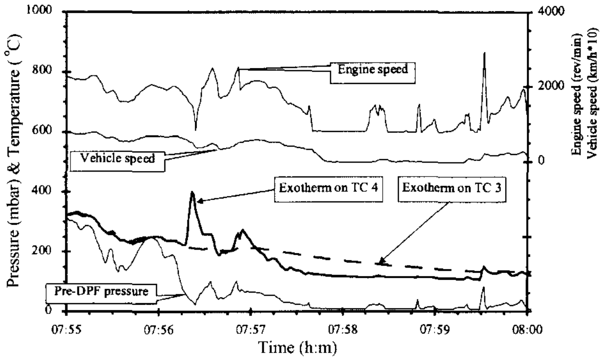

Figure 5. Regeneration with ceramic fibre DPF.

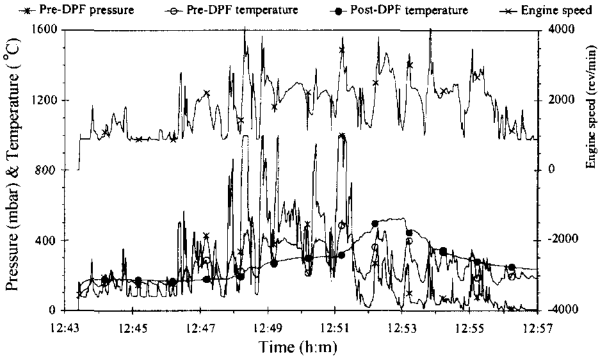

Figure 6. VW Golf TDI SiC DPF.

was about 400°C. This temperature was a function of the vehicle and engine speed, and confirms that no control system was in use to procure regeneration, which was entirely spontaneous. Over the 5000 km test duration, a total of 17 regeneration events occurred. With the Cordierite DPF, there was evidence that some regeneration events occurred at temperatures between 250 and 310 °C.

2.2.2. Peugeot 306 – ceramic fibre DPF test data

Figure 5 shows an example of a regeneration event in the ceramic fibre DPF, while the vehicle was operating at relatively low speed in a city environment. Engine and vehicle speed traces depict the transient low speed city conditions. Load corresponds to road load for the vehicle.

Figure 5 shows a clear exotherm indicated by a thermocouple, (TC4), fitted into the matrix of the ceramic fibre DPF, towards the front face. Vehicle speed at the time of regeneration was about 50 km/h, and engine speed in the range 1500-2000 rev/min. Despite this low load condition, regeneration occurred in the DPF at a temperature in the range 220-225°C (Richards *et al.*, 2000). During the 5000 km test, 47 regenerations were identified from instrumentation traces. This type of filter appears to regenerate more frequently, and at lower temperatures than the solid monolith type of ceramic filter.

2.2.3. VW Golf – SiC DPF test data

Figure 6 shows an example of a regeneration event in the SiC DPF, while the vehicle was being driven in a city environment. Figure 6 shows that prolonged high speed operation is not essential to bring about a regeneration event. Despite the low ambient temperatures of mid winter, (estimated at 6-10°C for 1st February in the UK), and the fact that the car had started from cold only at 12.43 pm, regeneration occurred after operation for only about 8 minutes at 12.51. Although load is nominally given by road load, vehicle acceleration increases fuel supply considerably, thereby raising exhaust gas temperatures.

Regeneration occurred between traffic islands in a city environment, immediately after acceleration followed by deceleration, which is typical of much city driving. The pre-DPF temperature just prior to regeneration was about 450°C, and the peak downstream temperature resulting from the exotherm was about 500°C. Pressure reduction from soot burn-out occurred over about one minute, although temperature decay after the exotherm was slower. The time for the downstream temperature to decay from peak value to normal levels was about 3 minutes. Over 50,000 km of operation, regeneration has occurred typically every 400-600 km in the passive DPF. There has been no occasion when the car has been unable to operate because of soot accumulation, and regeneration events have been quite regular and predictable based on exhaust system pressure at idle.

Emissions test data obtained with the car demonstrate a fairly consistent pattern of behaviour as is shown in Figures 7 to 9. Emissions tests were carried out in triplicate, using the European city plus extra urban drive cycles (ECE plus EUDC) protocol.

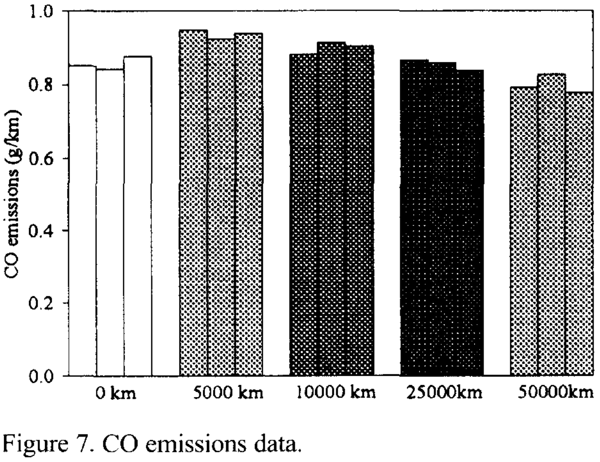

Figure 7. CO emissions data.

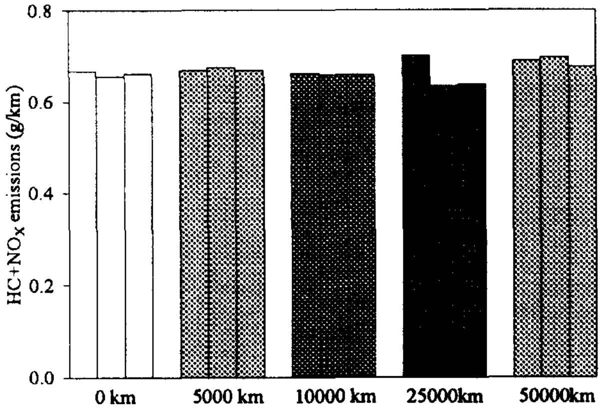

Figure 8. HC + NOx emissions data.

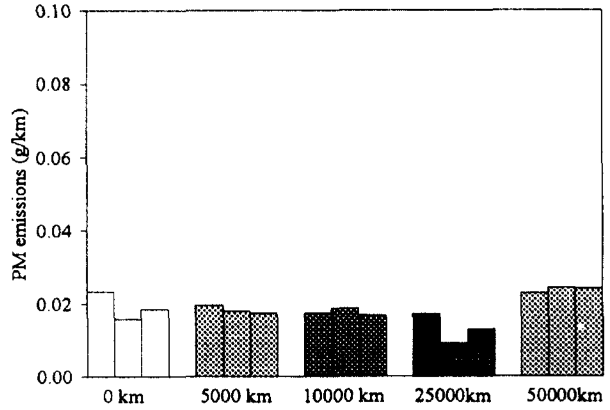

Figure 9. PM emissions data.

Figures 7–9 show that emissions levels generally changed little throughout the 50,000 km road trial. Despite removal of the oxidation catalyst to facilitate the fitting of the DPF into the exhaust line, all gaseous emissions still met the relevant European legislation for this vehicle at the end of test (CO: 1.0 g/km, HC + NOx: 0.9 g/km). Particulate emissions, as a result of fitting the DPF, not only met the original maximum permitted level of 0.1 g/km, but generally met the future Euro IV emissions limit of 0.025 g/km scheduled for 2005. Data for the 50,000 km measurement show a slight increase above the 0.025 g/km limit, but there was no obvious physical deterioration of the SiC DPF, and the reason for the slight increase is not known. Work with this vehicle is planned to continue to take the trial distance to 80,000 km, including further emissions assessments.

Figure 10 shows that over 50,000 km, fuel consumption remained remarkably constant. The final result, measured after 50,000 km, differed by less than 2% from the value recorded immediately after the DPF was fitted to the vehicle.

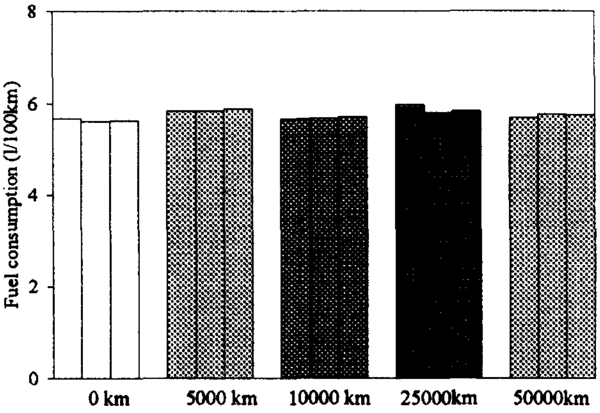

Figure 10. Fuel consumption, *l*/100 km.

All fuel consumption results were computed by carbon balance on data obtained during emissions testing. This procedure is recognised as providing an acceptably precise technique for determining fuel consumption. Fuel consumption is clearly a very important factor when fitting a DPF. The trap will retain metallic emissions from the engine, derived from wear metals, and metallic lubricant additive formulations, and will also retain sulphates formed from combustion of sulphur in the fuel, together with metallic products of combustion derived from the fuel additive used to assist regeneration. It is therefore important that sulphur levels in the fuel should be limited, although the fuel additive technology is not itself adversely affected by the presence of sulphur in the fuel. All the vehicle test work was carried out on diesel fuel containing approximately 430 ppm wt sulphur. It is also important to use an additive at as low a dose rate as possible, to minimise contributions to residual back pressure in the DPF. Consistent, reliable regeneration with a totally passive DPF was demonstrated using a metal treat rate of only 20 ppm wt during the 50,000 km test. This low metal dose rate was a significant factor in the low residual DPF back pressure increase, and resulting small change in fuel consumption over the trial. No-harm tests were carried out at the Institut Francais du Petrole (IFP) with a VW Golf having the same type "B" engine as the vehicle used for performance testing. This vehicle was equipped with a Cordierite DPF, but used the same iron/strontium metallic additive at a treat rate giving 20 mg/kg metal in the fuel.

Particle size measurements were carried out using scanning mobility particle sizer (SMPS) equipment. Data obtained at 50 km/h comparing numbers of fine particles recorded with and without fuel additive and with and without DPF are shown in Figures 11 and 12 (Vincent *et al.*, 1999). In both Figures, repeated results are shown by

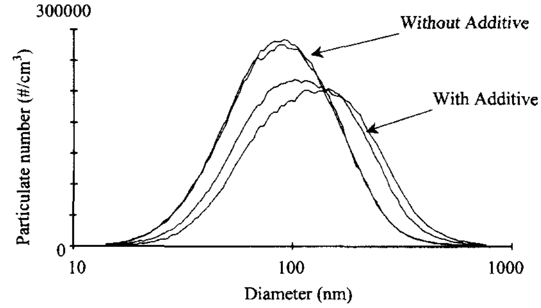

Figure 11. Particle size measurements made at 50 km/h : no trap.

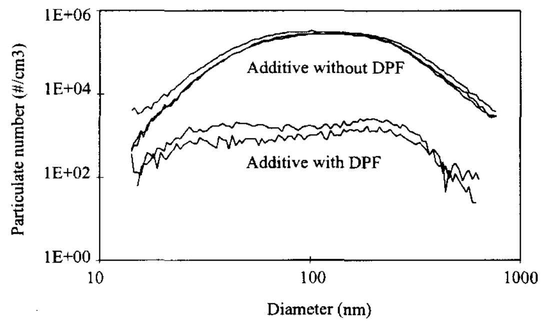

Figure 12. Particle size measurements made at 50 km/h : additive treated fuel.

two separate traces for the different test conditions.

Figure 11 shows that the presence of the metallic fuel additive in the fuel has no adverse effect on particle size distribution where no DPF is fitted. The number of particles detected is shown on a linear scale. The maximum number of particles is reduced, and the mean particle size increases slightly with additive treated fuel. This result is consistent with the elimination of the smallest particles when the additive is present in the fuel.

Figure 12 shows results obtained using additive treated fuel, comparing the number of particles measured with and without a DPF. As might be expected, fitting the DPF reduces the number of fine particles by up to about 2 orders of magnitude, without changing the overall size distribution. In addition to reducing the mass of particulate emissions by about 80-90%, the number of fine particles is reduced by over 90% by the DPF. These factors taken together constitute major potential health benefits from cleaner air, from the use of DPF technology combined with low dose metallic fuel additives to assist regeneration.

2.3. Vehicle Testing-Truck and Bus

Work was carried out on a light truck fitted with an engine of type "C", details of which are given in Table 1. The vehicle was initially tested with a SiC DPF, and for later tests this was replaced with a ceramic fibre filter. All testing was carried out on a chassis dynamometer, using a simulated city drive cycle, representative of operation in Seoul. The drive cycle is shown in Figure 13. Load corresponds to road load plus acceleration against a representative inertia for this dynamometer test.

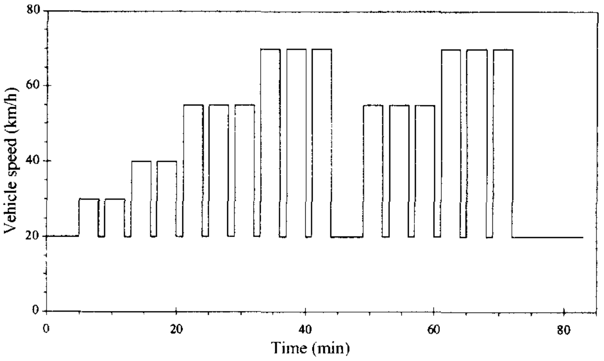

Figure 13. City drive cycle: Seoul.

2.3.1. Renault truck test data

With the light truck, whose engine represents older technology, dating from 1990, reliable regeneration could be obtained in purely simulated city drive operation with both the DPF types tested. Regeneration was assessed using purely passive DPFs. Traces from tests carried out with the 6 litre volume SiC DPF are shown in Figure 14. Results for the ceramic fibre DPF are shown in Figure 15.

Extensive dynamometer testing was completed with fuel containing 200-300 ppm sulphur. During the tests, additive treat rate was reduced from the normal 20 ppm metal to levels below 10 ppm. At these lower metal treat levels, a trend towards increased mean back pressure was observed.

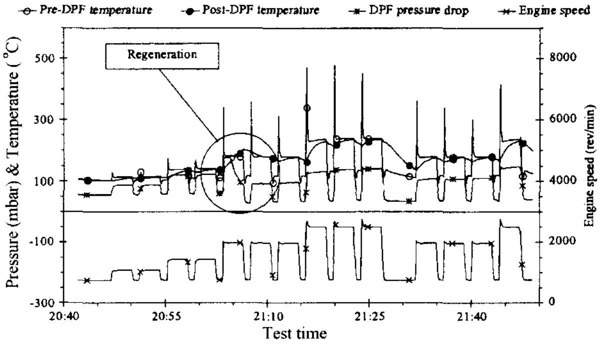

Figure 14. Renault truck data: SiC DPF.

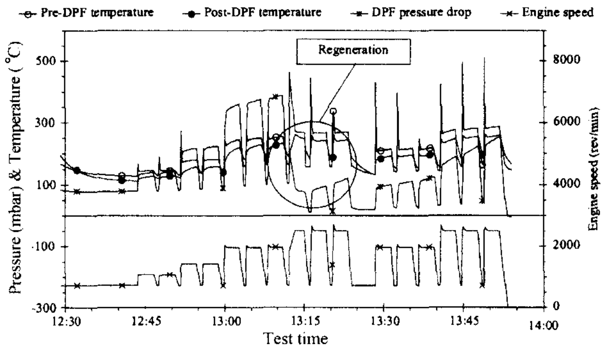

Figure 15. Renault truck data: ceramic fibre DPF.

2.3.2. City bus test data

A city bus trial was carried out in the UK in 1999 over a period of 33 days, and covering a distance of over 3,500 km of mainly inner city routes (Southgate, 1999). The vehicle was a 1987 Optare Metrorider bus powered by a naturally aspirated engine of type "D", whose details are given in Table 1. The vehicle was fitted with a passive 9 in x 9 in Cordierite type EX 66 DPF, and operated on fuel containing combined iron/strontium additive at a treat rate giving 20 ppm metal in the fuel. Fuel with a sulphur content of 50 ppm wt, and specific gravity of 0.835 was used in the test. The vehicle had covered 692,615 km at the start of the test, and 696,186 km at the end of the test. Smoke measurements recorded for some months prior to the test, and during the test after fitting the DPF are given in Table 2.

The bus was fitted with a data logger recording DPF inlet and outlet temperatures and exhaust back pressure. Recordings were made on 7 separate days during the trial, as shown in Figure 16.

The higher back pressure and temperature conditions recorded on 5th September resulted from higher vehicle speeds. City traffic variations alter in an irregular pattern, and on some days traffic density was greater, which explains observed lower system temperatures and pressures resulting from low vehicle speed. August 31st was a National Holiday, when traffic density would also have been low, leading to the observed higher system temperatures from increased vehicle speed. Apart from data recorded for 31st August, 5th September, and for 28th September, exhaust temperatures were generally in the region of 300°C. System back pressures generally lay in the 60 mbar region, except for data recorded on 5th September, and 20th September. Exhaust system pressures recorded on different days show variations resulting from changes in traffic density. Generally, mean values for pre-DPF pressure lay in the region of 60 mbar. Recorded temperatures also varied with traffic density. Values ranged from about 300 to peak levels of over 500°C.

Table 2. City bus smoke data.

Date	Smoke reading (K)
February 1999	0.99
April 1999	0.79
May 1999	0.78
June 1999	0.97
July 1999	0.93
August 1999	1.61
September 1999	0.24*

*After fitting DPF

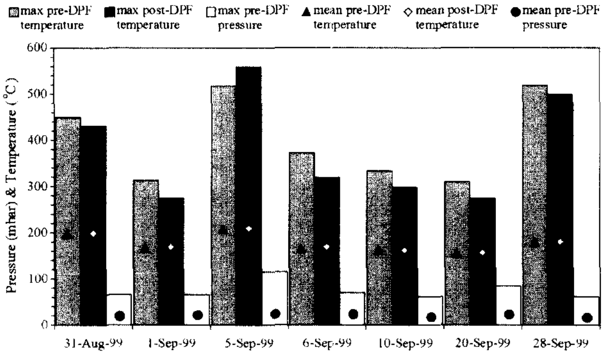

Figure 16. Combined temperature and pressure data recorded on 7 different dates.

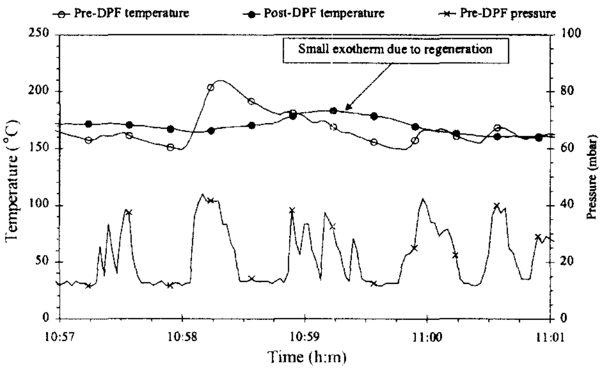

Figure 17. Regeneration recorded on 1st September 1999.

Vehicle performance was considered to be unaffected by the DPF; the only comments made by drivers were positive in respect of the low smoke emissions.

Figure 17 shows a regeneration event recorded on September 1 1999. As indicated in Figure 16, the recorded DPF pressure was quite low, in the region of 60 mbar, and perhaps because of this, the regeneration event does not show significant pressure reduction. An additional factor is likely to be the mass of soot accumulated immediately prior to regeneration. Where regeneration occurs with a relatively small mass of accumulated soot, the reduction in system pressure resulting from regeneration can be quite small. However, the on-board data logger clearly recorded an event during which the downstream temperature exceeded the upstream temperature. This is consistent with an exothermic reaction which results from carbon burnout. Overall, the trial was regarded as very successful, particularly bearing in mind the age of the vehicle, the generally high level of smoke and particulate emissions, and the mainly low speed city operating environment. The implications are that this type of simple DPF system, relying on a fuel soluble additive catalyst for regeneration, would be very well suited to retrofit applications. For these applications, a simple, robust and reliable particulates reduction system appropriate for older vehicles is needed.

3. CONCLUSIONS

Extensive bed engine testing demonstrated excellent regeneration performance from a fuel additive in a simple passive diesel particulate filter (DPF). The organometallic additive, based on a combination of iron and strontium, was used at a treat rate giving 20 ppm metal in diesel fuel meeting EN 590 (sulphur limit 500 ppm wt). No harm emissions testing showed that there were no adverse side effects on the number of fine particles from the use of the metallic additive. Data showed reduced numbers of the smallest particles for additive treated fuel even without the DPF. The combination of fuel additive and DPF showed reductions of over 90% in the number of ultra fine particles emitted.

Performance tests with a number of vehicles, ranging from passenger cars to a light truck and a city bus, showed excellent regeneration performance from the combination of a simple passive DPF and a low dose rate fuel additive to catalyse soot regeneration.

One test vehicle was operated for 50,000 km on the road in order to demonstrate long term reliability. Emissions and fuel economy were maintained largely unchanged over the test distance for this vehicle.

A light truck and a city bus were operated with the same simple DPF system, and the same low additive treat rate, and showed successful DPF regeneration in actual city traffic operation, or in simulated city centre driving executed on a chassis dynamometer.

Overall, the combination of a simple DPF with a highly effective fuel additive, has shown itself to be an entirely viable technology for simple and reliable retrofit use. Major benefits, from very significant reductions in particulates emissions in older technology engines, have been demonstrated. This technology does not require the use of ultra low sulphur diesel fuels.

ACKNOWLEDGEMENTS–The authors gratefully acknowledge the assistance of others in preparation of this paper. Mons. Jean-Baptiste Dementhon and Mme. Brigitte Martin from IFP provided data from tests carried out in France. Mr. Bill Southgate of Engine Control Systems Ltd. carried out an evaluation of the fuel additive in a city bus in the UK, writing a report which was provided to the authors. Data from this report has been used in the paper.

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