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ABSTRACT

A novel dosing system for fuel borne catalyst (FBC), used to assist regeneration with a diesel particulate filter (DPF), has been developed. The system was designed for on-board vehicle use to overcome problems encountered with batch dosing systems. Important design features were simplicity, to minimise system cost, and the use of in-line dosing rather than batch dosing linked to tank refuelling.

The paper describes the development of the dosing system which continuously doses FBC into the fuel line feeding the engine injection pump. The theoretical considerations behind the concept are explored, together with the realities imposed by fuelling regimes in which a variable proportion of the fuel flowing through the injection pump is passed back to the fuel tank. Two types of system are considered, ie where 1) FBC is added to the fuel in direct proportion to the flow rate of fuel and 2) FBC is added at a constant time-based rate. Modelling of changes in the concentration of FBC in the fuel over time indicated significant non-linearity with both approaches.

Bed testing with a diesel engine equipped with a DPF assessed both flow-based and time-based dosing concepts. The test work demonstrated that the in-line FBC dosing concept could achieve reliable regeneration with either system. The averaging effect of soot accumulation over time on the ratio of metal to soot within the DPF apparently accounts for successful regeneration despite big variations in FBC concentration.

The paper describes the application of the system to light duty vehicles such as Black Cabs used in central London. Data loggers indicated successful operation on several vehicles over distances ranging from 12,000 to 20,000km. An in-line FBC dosing system was also fitted to a heavy duty fire appliance support vehicle for additional tests. Data to date suggest that this application has produced acceptable DPF regeneration performance. Test work on this vehicle continues.

INTRODUCTION

The use of a DPF system, fitted as original equipment, and employing an FBC to assist regeneration, has been described in detail in a fairly recent paper (1). Over 250,000 such systems are now operating on passenger cars, mainly in Europe, and the system has demonstrated the practicality and reliability of the use of FBC as a means to secure regeneration. The DPF system naturally requires a mechanism for dosing FBC into the fuel for continued operation. A batch-type system is employed, dosing FBC into the fuel following re-fuelling. There are three aspects to the functioning of this type of system:

- detection of the refuelling event
- calculation of the correct dose of FBC for addition to the fuel
- delivery of the calculated volume of FBC into the fuel in the tank

Consideration of a simple level sensor in a fuel tank readily indicates that vehicle dynamics, i.e. acceleration, braking, ascending or descending inclines, and cornering, all have the potential for interpretation as a refuelling event. This is particularly true in modern diesel passenger cars, where fuel tanks tend to be located under the vehicle floor, and are often very irregular in shape. This can give rise to significant fuel surge in service, particularly where the tank contains certain critical fuel volumes. The adoption of irregular tank shapes to optimise vehicle packaging, has also created significant problems of non-linearity, and dead-bands, for the level sensor. These represent additional obstacles to accurate calculation of the volume of fuel added after a refuelling event.

Reliable detection of the refuelling event in the PSA 607 which pioneered the use of the DPF in production passenger cars, was solved by fitting a special filler cap with micro-switch contacts, although this is not stated in reference (1).

Original equipment (OE) DPF systems tend towards complexity, resulting from a desire to ensure total reliability, and high customer satisfaction. This increases cost, although even the high costs of a complex system can be reduced through investment in appropriate volume production technology. A recent Renault patent covering the batch dosing system for a fuel additive used in conjunction with a DPF, demonstrates the complexity of the system integration needed for a reliable OE exhaust after-treatment system (2).

For retrofit applications it is frequently not appropriate to use highly complex systems, because production volumes are generally small compared to OE volumes. Retrofit DPF systems may be applied either to new vehicles which were not fitted with exhaust after-treatment at the factory, or to older vehicles which need exhaust after-treatment to operate in specified locations. In either case, the cost of the retrofit system is an important consideration.

Reliability is no less important for retrofit systems, so the challenge is to build a DPF system which has an acceptable cost and which provides a very high degree of reliability. Previous papers have shown the feasibility of retrofitting even light duty vehicles with DPFs, where an FBC is employed for regeneration (3,4). However, none of these vehicles was fitted with a dosing system. Pre-dosed fuel was used for this test work, typically employing a metal content of about 20mg/kg of fuel.

Where a batch-type FBC dosing system is used for retrofit systems, it is difficult to meet the dual requirements of low cost with high reliability. Low cost design suggests a simple system of potentially low reliability, while high reliability is likely to require a complex system of high cost, without the benefits of very large production numbers over which to amortise investment for production tooling. Also, installing a batch-type system requires calibration of the tank level sensor to ensure accurate dosing with irregular tank shapes. This is likely to result in relatively costly installation procedures.

DOSING SYSTEM DESIGN PHILOSOPHY

To resolve this problem, a novel approach was adopted for a development dosing system. Instead of batch dosing FBC into the fuel tank after the refuelling event, the approach adopted was to dose FBC directly into the fuel line feeding the engine injection pump. Dosing is nominally continuous, although in practice a technique of constant volume pulsing at very low frequency was employed. This approach resolves the issues of detecting the refuelling event, and eliminates the need to calculate the volume of fuel added to the tank. In-line dosing also overcomes potential multiple dosing problems which can result from fuel surge, with batch dosing systems.

However, major problems remain as follows:

- a substantial and variable amount of the total fuel volume pumped returns to the tank from the injection pump. The return volume typically lies between about 75% of the total pumped volume at high load, and about 90- 95% at idle.
- with a system dosing all the fuel entering the injection pump, repeated dosing of fuel with FBC will occur, since some fuel will pass many times through the injection pump. In consequence, as fuel is depleted in the tank, the remaining fuel acquires a steeply increasing FBC concentration, through repeated dosing.

Thus with an in-line dosing system, the precise concentration of FBC in the fuel varies with engine speed and load. In addition, depending on the amount of fuel in the tank, the net concentration of FBC will vary quite sharply over time. It is necessary to reduce the FBC nominal dosing rate, to allow for the high rate of return flow to the tank. Depending on operating conditions, a mean time-averaged return flow to the tank could be set at about 85%. This would require a net dosing rate of about 15% of the desired FBC concentration, i.e. a reduction by a factor of about seven in the desired dosing rate.

However, starting from a full tank of fuel, initial FBC dosing rate into the fuel supplied to the engine would be very low indeed, i.e. in the range 12 - 15% of the desired treat rate, depending on engine speed and load. In practice, this means an initial fuel metal content of perhaps 2 - 3 mg/kg. As fuel level falls, multiple dosing of fuel returned to the tank increases concentration over time.

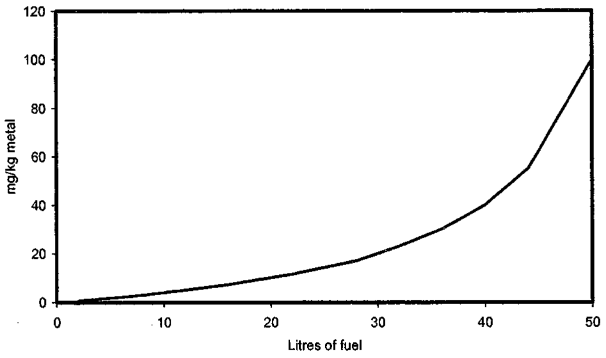


Figure 1. Metal concentration change with fuel consumed

When the tank is nearly empty, the remaining fuel contains a very high level of FBC (equivalent to perhaps 60-100mg/kg metal) as a result of multiple dosing. The concentration profile as a function of tank volume is therefore very non-linear. A simple calculation shows that this concentration profile has the form indicated in Figure 1. At first sight, this appears to be a significant disadvantage for the in-line dosing system concept. However, it is important to consider how the fuel borne catalyst actually functions in the DPF. To produce the

FBC, one or more metals, for example iron and strontium, are reacted chemically with hydrocarbons, to make up fuel soluble organo-metallic molecules.

During the combustion process, the hydrocarbon portions of the organo-metallic molecules burn, leaving mainly iron oxide with strontium salts in finely divided form. The iron oxide/strontium salt particles combine with the soot particles which typically form during the combustion process. The soot particles emerging from the engine in the exhaust gas thus contain iron oxide/strontium salts broadly in the proportion in which the FBC was added to the fuel. As fuel metal concentration varies, the soot trapped in the DPF contains a correspondingly varying level of metal.

With an FBC to assist regeneration, the DPF accumulates soot over time, before periodic regeneration. Previous work has shown that the DPF accumulates soot for significant periods prior to regeneration (3,4). As a result, the DPF can be regarded as a device which averages the ratio of metal to soot over time. Commercial DPF systems employing an FBC to aid regeneration have traditionally striven to ensure that the engine is supplied with fuel containing a constant concentration of FBC. However, previous work (5) showed that the key parameter influencing the combustion of accumulated soot appears to be the ratio of metal to soot. More rapid regeneration results from a higher ratio of metal to soot (5).

However, the amount of soot produced per unit of fuel burned varies with engine operating conditions. It therefore follows that the metal to soot ratio must also vary, even where a constant fuel concentration of FBC is employed. It was postulated that a key factor for DPF regeneration is the increasing metal content of the soot trapped within the DPF over time, as fuel is consumed. If the approximate average FBC concentration in the fuel resulting from multiple dosing, is satisfactory, then an appropriate rough average metal to soot ratio will be achieved.

Furthermore it was recognised that in practice, the in-line dosing system would lay down increasingly metal-rich layers of soot in the DPF as tank level dropped. It was expected that this feature of the system would bring light-off advantages to compensate for the initially low metal content of soot produced soon after refuelling. It was believed that regeneration should be achievable despite having both a variable FBC concentration and a variable metal to soot ratio, because of the averaging effect of soot storage within the DPF.

SYSTEM MODELLING

With the in-line dosing system proposed, when the fuel tank level is high, and fuel metal content is low, soot with a low concentration of metal accumulates in the filter. As the tank level falls and the fuel metal content rises, the metal content of soot trapped in the DPF increases correspondingly. The aim of the dosing system was to achieve a long term average fuel metal content of about 20mg/kg, as achieved by pre-mixing or in-tank batch dosing. As discussed earlier, success for this system required that significantly non-linear FBC content with time should not inhibit effective DPF regeneration.

Whether non-linear dosing would permit satisfactory long term average fuel metal contents to be achieved was tested by a simple mathematical model which allowed for specification of:

- minimum and maximum fuel feed rates
- minimum and maximum fuel return rates
- fuel tank volume and refuelling strategy
- change in the rate of addition of FBC into the fuel

Simulations of the variation in fuel metal content with the amount of fuel in the tank, and of the mean fuel metal content over time are shown in Figure 2. For this simulation, the following variables were chosen:

- minimum injection pump fuel feed rate : 7.5kg/hr
- maximum injection pump fuel feed rate : 23.4kg/hr
- minimum returned fuel percentage : 75%
- maximum returned fuel percentage : 95%

The amount of pump fuel feed returned to the tank varies with engine speed and load. In the model, random number generation was used to simulate engine speed and load variation. The fuel tank data used in the model were:

- tank volume : 80 litres
- refuel level maximum : 10 litres remaining
- refuel level minimum : 5 litres remaining
- minimum volume added : 35 litres

A second random number routine was used in the model to simulate the tank level (between 5 and 10 litres remaining) at which refuelling occurred. The model was intended to simulate both the variation in actual road vehicle operation, and in refuelling habits.

The calculation used in the model was a simple step-wise routine based on a time interval of 6 minutes. In the simulation shown in Figure 2, FBC is added at a constant metal treat rate of 3.8mg/kg of fuel. Tank level and fuel metal concentration are calculated over 100 hours operation as fuel is consumed and replenished.

Figure 2 shows a repeated saw-tooth pattern of fuel metal concentration changes with falling tank levels followed by refuelling. Figure 2 also shows the computed mean fuel metal content over 7 refuelling cycles during which the fuel tank is almost emptied, and is then refilled close to its maximum level.

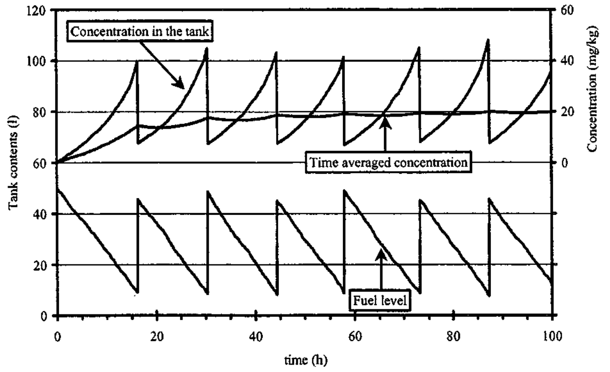


Figure 2. Simulated variation in metal content over time

Selection of different values for the various parameters in the model allowed simulation of different driving patterns and refuelling strategies. Figure 3 shows the effect of a more random tank filling strategy for the same fuel and FBC treat rate parameters. In Figure 3, the following refuelling parameters were used in the model:

- refuel level maximum : 15 litres remaining
- refuel level minimum : 5 litres remaining
- minimum volume added : 10 litres

The actual volume added in this computation was determined by a third random number generation routine. The intention was to simulate a refuelling strategy more representative of actual vehicle usage patterns.

As can be seen from Figure 2 and Figure 3, differences in refuelling strategies have a negligible effect on the time averaged concentration of FBC, although the shape of the patterns of metal concentration and tank volume differ significantly.

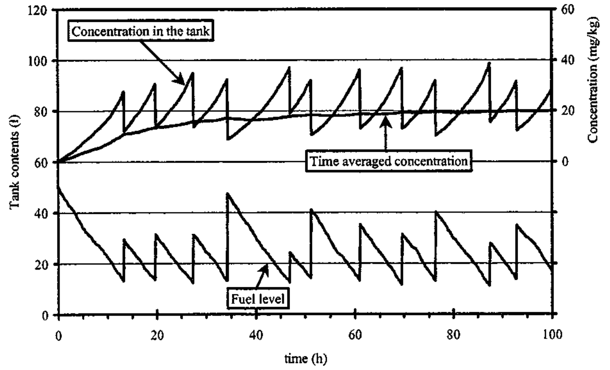


Figure 3. Simulation with random refuelling strategy

ENGINE TEST WORK

It was postulated that the DPF would behave as an averaging device, reducing variation in the soot : metal ratio of trapped soot. On this basis, soot burn-out characteristics using the in-line dosing system, with its inherently variable concentration effect, were expected to be broadly similar to those for a constant fuel metal concentration. This aspect was critical to success however, and needed to be demonstrated. Test work was set up accordingly, using a previously tried and tested bed engine protocol (6). The engine employed for the test work (engine A) was a 1.9 litre indirect injection (IDI) naturally aspirated passenger car diesel engine. Details of engine A are given in Table 1.

Table 1. Data for test bed and test vehicle engines

Code	A	B	C
Configuration	IDI Nat Asp	IDI Nat Asp	DI Turbo
Type	XUD 9A	TD 27	D6 A180
Bore, mm	83	96	98.4
Stroke, mm	88	92	120
Displ., cm^3	1905	2663	5480
Comp. Ratio	23.0:1	21.8 :1	19.0 :1
Max.power, kW	52	64	132
Maximum power speed, rev/min	4600	4300	2400
Max.torque, Nm	120	175	550
Maximum torque speed, rev/min	2000	2200	1550

The general bed engine test set up has been more fully described in an earlier paper (6), but in brief, the bed engine drove an eddy current dynamometer under controlled conditions capable of maintaining any desired speed and load. Certain selected speed and load conditions were used to allow comparison of regeneration performance with previous results obtained using fuel pre-dosed with a known concentration of FBC. The FBC used for the test work was Octel Octimax™ containing organo-metallic iron and strontium compounds mixed to give a ratio of 4 parts iron to one part strontium. Other test work using this additive has been reported previously (3-5).

A Corning cordierite DPF was employed for the test work. This unit was 5.66 inches (144mm) in diameter by 6 inches (152mm) in length, giving a volume of 2.48 litres. Other details of the DPF material used are given in Table 2. The DPF unit was mounted in a suitable stainless steel welded can and fitted into the exhaust line using commercially available welded clamp rings, for ease of assembly. The test fuel used met EN 590 specification for diesel fuel. Fuel sulphur content was 45ppm, representative of commercial automotive diesel fuel in the UK. Further details of the test fuel used (coded ULSD 3) are given in Table 3.

Table 2. Details of DPF materials used for testing

Property	Cordierite	Silicon Carbide
Cells per cm^2	16	14
Porosity, %	46	45
Wall thickness,mm	0.43	0.8
Mean pore size, μm	33	29
Thermal conductivity @ 25 ° C (W/mK)	< 0.5	11

Although IDI engine technology is now obsolete in Europe, a substantial data base existed from previous test work with the type A engine. The DPF regeneration characteristics measured with pre-treated fuel of constant metal concentration, at different set point conditions, were extremely well documented as a result. The test engine thus represented an excellent tool to assess whether the variable fuel metal concentration produced by the in-line dosing system would permit reliable regeneration under controlled conditions. In order to assess this, the fuelling arrangements normally employed within the engine test cell were altered to simulate an on-road vehicle arrangement.

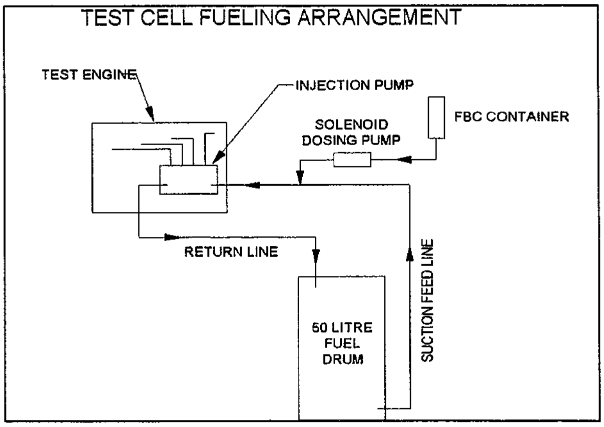
A 50 litre fuel drum was installed in the engine test cell and arranged with a feed pipe to the inlet side of the engine injection pump. The return pipe from the spill side of the injection pump conveyed unused fuel back to the drum.

Table 3 Details of ULSD 3 test fuel used.

Parameter	Value
Density, kg/litre @15 ° C	0.835
Viscosity, cSt @ 40 ° C	2.79
Sulphur content, mg/kg	45
Distillation	
Initial boiling point, ° C	176
50% vol @ ° C	274
95% vol @ ° C	345
Final boiling point, ° C	356
Lubricity, HFRR WSD μm	402
Cetane number	53.5

This arrangement simulated the fuelling system on a road vehicle. Between the tank and the suction side of the engine injection pump, a dosing device was installed, so that all fuel entering the injection pump was treated with the metal based FBC. The arrangement is shown in Figure 4. Fuel samples were taken at intervals to measure actual metal content as a function of tank volume.

Figure 4. Test cell fuel supply system.



MECHANICAL FLOW-PROPORTIONAL DOSING

Initial engine tests were performed using a mechanical device which dosed FBC in proportion to the fuel flowing through the valve. A number of difficulties were experienced with this device, most of which were associated with the low FBC flow rate required. As discussed earlier, using the in-line dosing approach with its multiple dosing effect, reduced the actual FBC dosing rate by a factor of 7 or 8. As a result, the volume of FBC added to the fuel is very low on a continuous flow basis, and this necessitated extremely fine clearances in the mechanical dosing device. The tests showed that the desired dosing rate was not being achieved with the mechanical device, so the tests were halted. The concept of flow proportional dosing was neither proved nor disproved, but the difficulties of controlling such minimal flows of FBC forced a re-assessment of the dosing process.

ELECTRICAL FLOW-PROPORTIONAL DOSING

An electrically operated dosing system based around a small 12volt solenoid driven pump was designed as a replacement for the mechanical dosing device. This system overcame the problems encountered with the mechanical device, by setting the frequency of operation of the solenoid to match the required flow rate. The flow rate of FBC was in fact so low, that the solenoid pulse frequency was well below 0.1Hz, even at high engine speed conditions. The discrete volume delivered by the solenoid pump was repeatable and well controlled, as shown by separate pump delivery tests off the engine bench. Fuel flow rate was established using a positive displacement turbine meter, with electrical output. An electrical circuit provided a pulsed current to the solenoid at a frequency calculated from the output of the turbine meter. This technique appeared to have resolved the delivery control problems previously encountered.

The bed engine (type A) previously employed for the tests with the mechanical dosing device was used again, but with the solenoid pump FBC dosing system in place of the mechanical device.

It was known from previous work that a lower active metal content in the fuel could lead to higher DPF back pressures, and a reduced tendency to achieve regeneration. The inherent characteristics of the in-line dosing system dictate a low metal concentration in the fuel when the tank is full, with metal content rising as fuel level falls. It was therefore expected that initially, regeneration would be delayed, and that DPF back pressures would be higher than for operation with FBC pre-mixed at the optimum concentration in the fuel. All previous successful test operation with the bed engine had been carried out using pre-mixed fuel containing a known and fixed level of metal.

The engine was initially operated with pre-mixed fuel containing different levels of FBC, and the back pressure and regeneration traces monitored, to assess the effect of changing the level of metal in the fuel. Tests were initially run with fuel containing constant or fixed levels of 10mg/kg and 20mg/kg of metal. The engine speed and load conditions were 1260 rev/min, torque 5Nm. These traces are plotted in Figure 5.

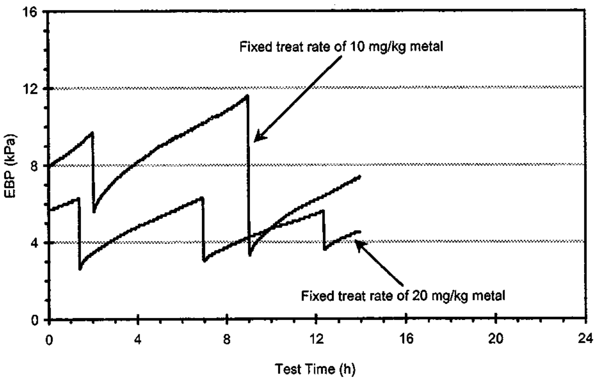


Figure 5. Effect on back pressure of high and low metal concentrations in the fuel: pre-treated fuel

It is clear from the traces shown in Figure 5, that fuel metal content has a noticeable effect on the DPF pressure and regeneration behaviour. With a fixed or constant metal concentration of 20mg/kg, exhaust back pressure was markedly lower than when a concentration of only 10mg/kg of metal was used in the fuel. In addition, the DPF showed a clear trend to more frequent regeneration with the higher metal content. These two tests were run as a reference, to assist in interpreting the regeneration performance produced by the in-line dosing system. It was known that this would produce a metal to soot ratio varying with time.

The engine was subsequently operated at the same speed and load conditions with the electrical dosing system, running from the simulated vehicle fuel tank set-up shown in Figure 4. To set test conditions, the computer model was used to determine FBC dose rate, assuming a mixed regime of road conditions, with the aim of achieving a stabilised or long-term mean metal treat rate of 20mg/kg in the fuel. The following parameters were set for the test run:

- fuel flow of 20kg/hr (mean calculated for mixed duty)
- dosing frequency : one pulse every 285 seconds
- solenoid pump volume per pulse : 0.07ml
- calculated fuel metal content (first pass) ~2mg/kg

For the operating conditions selected, low engine load produced high fuel return flows to the tank. This resulted in a time averaged metal concentration of about 25mg/kg, which was above the nominal 20mg/kg desired.

The initially low metal concentration resulting from the in-line dosing system delayed regeneration, as is clear from Figure 6. For the first 12 hours of operation, higher than normal soot build up and back pressure increase were observed. However, as the tank fuel level fell, and fuel metal content increased, there was a marked increase in the frequency of regeneration, and a downward trend in exhaust system back pressure. Figure 6 shows both the delayed initial regeneration and subsequent increasing regeneration frequency as fuel metal content increased.

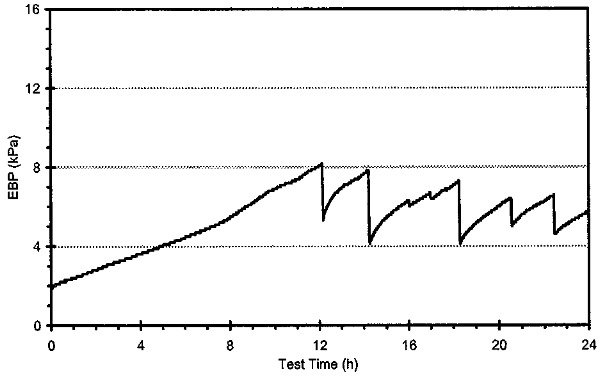


Figure 6. Variation of DPF back pressure with time: dosing system operation.

The change in regeneration behaviour could be clearly traced to fuel metal content, by means of fuel samples taken while the engine was operating. The low load and speed of operation allowed the engine to operate for 24 hours on the tank volume of 50 litres of fuel. Figure 7 shows fuel metal content established by laboratory testing samples taken at intervals from the test cell fuel tank.

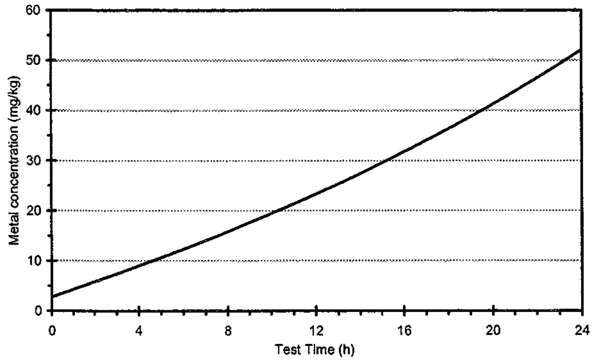


Figure 7. Fuel metal content variation with tank level : data from samples taken during bed testing.

The increase in metal content over time, as tank fuel level fell, is clear. The similarity of the measured fuel metal concentration with the computed variation in metal content shown in Figure 1, is interesting. Regeneration first occurred with the in-line dosing system after about 12 hours of operation. By this time, the fuel iron concentration had risen, through fuel depletion in the 50 litre tank, to a level of about 24mg/kg. Mean metal content over the 24 hours of operation was approximately 25mg/kg. Figure 7 does not show the effect of refuelling on fuel metal content, however. Fuel usage was very low, at the 1260rev/min, 5Nm setpoint, and the test was terminated without refuelling the 50 litre test cell tank.

In the next test, the engine was operated at a constant 2710rev/min and 30Nm torque, resulting in higher fuel consumption, and the need to refuel the test cell tank. The same FBC dose rate was employed as for the earlier run at 1260rev/min, 5Nm torque. However, at 2710rev/min and 30Nm torque, the higher speed and load resulted in a greater proportion of the fuel feed to the injection pump being consumed. Fuel return rates were thus reduced, with a consequent lowering of average fuel metal content below the computed 20mg/kg expected from simulated mixed driving conditions.

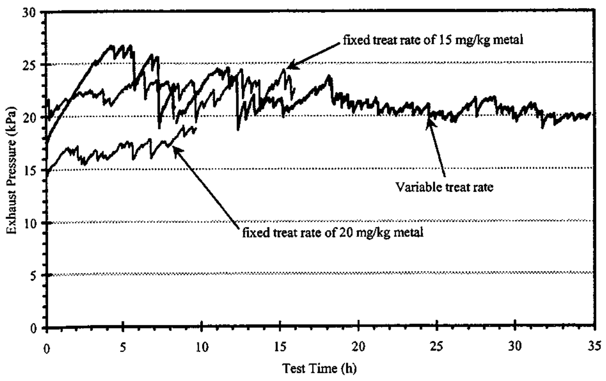


Figure 8. Pressure traces for fixed and variable fuel metal content

Figure 8 shows two traces corresponding to pre-treated fuel containing a constant or fixed 15mg/kg and 20mg/kg metal, and also a trace of DPF back pressure measured with variable metal content as produced by the in-line dosing system

Figure 9 shows the changes in metal content in the fuel, computed for the 30 hours of operation. During this time the tank in the cell was refilled three times with fresh fuel, resulting in major changes in fuel metal concentration.

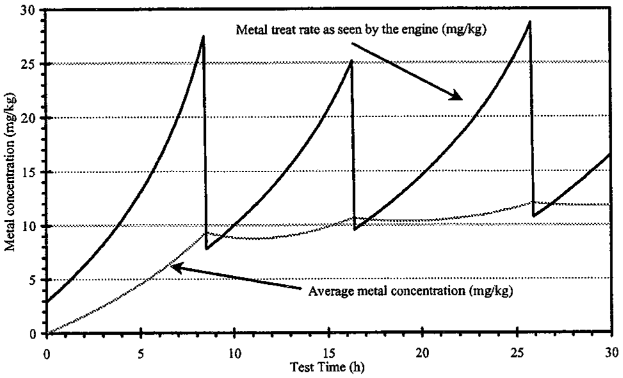


Figure 9. Change in fuel metal concentration with tank level change.

Inspection of Figure 9 after about 7 hours of operation shows that computed fuel metal content equated to about 20mg/kg. This rose steeply to peak at just over 27mg/kg before refuelling occurred at 8 hours. From the variable treat rate trace shown in Figure 8 we can see that regeneration activity increased significantly after about 6 hours' operation, leading to the first full regeneration after about 7.5 hours. This increased activity can be clearly linked to the higher metal content of soot being laid down in the DPF at this time

Figure 9 also shows the computed mean fuel metal content over the three refuelling events. Over time, the average fuel metal content tends to level out at about 12mg/kg, confirming the effect of sustained higher speed operation on mean fuel metal content. The shape of the DPF back pressure trace in Figure 8 obtained with variable metal treat rate, can be seen to reflect this, trending to a lower and more or less constant level at the end of the test. Interestingly, the variable treat rate back pressure trace in Figure 8 after about 25-30 hours of operation, which corresponds to the stabilised 12mg/kg metal level, is seen to provide slightly lower back pressures than were recorded with the fixed concentration pre-treated fuel containing 15mg/kg metal.

It is possible that the variable concentration achieved with the in-line dosing system gives some operational advantage through the periods of high fuel metal content when tank levels are low. These brief peaks of much higher metal content could be creating a more favourable environment for regeneration, leading to a lower overall DPF back pressure.

Overall, the engine test programme showed that despite the non-linear fuel metal concentration resulting from the use of the in-line dosing system, the time-averaging effect on the metal content of soot accumulated within the DPF allowed stochastic regeneration, or burn-out of the soot, within the DPF.

TIME BASED FBC DOSING

It was decided to simplify the dosing system concept even further, by assessing performance with purely time-based operation of the solenoid. The main benefit of this approach lay in the elimination of the need for fuel flow measurement. The electronic circuitry consisted of a unit capable of driving the solenoid with a widely variable frequency. The frequency of operation was no longer directly proportional to the flow of fuel to the engine, but determined simply by a pre-set pulse frequency. Potentially this system represented a universal design for all sizes of vehicles, since the only variable would be the timing of the electrical signal to the solenoid. Tests of the solenoid pump showed that at frequencies below about 10 Hz, delivery was proportional to the number of pulses. Since the frequency of pulsing, even with a very large truck engine, was less than one Hz, proportional delivery could be assumed.

The implications of such a simple mode of dosing FBC into the fuel were investigated, with interesting results. Injection pump characteristics generally are such, that at high speed and load, the volume of pumped fuel returned to the tank falls. The proportion returned to the tank may fall to 75% of the total pumped or possibly a little lower, depending on the pump application. Conversely at idle conditions, the proportion of flow returned rises to over 90%, and in some cases may exceed 95% of the total injection pump flow. Where a dosing system based purely on timed pulses is applied to an engine fitted with a DPF, the effect is to achieve variable dosing depending on vehicle operation.

In city traffic with a lot of idling, for example, where a very high proportion of the flow returns to the tank, a high concentration of FBC will build up in the fuel. By contrast, if a vehicle spends a lot of time at high speed, high load conditions, dosing concentration will tend to fall, because the volume of fuel returned to the tank is less than under lower load conditions. However, this variability in dosing should not constitute a disadvantage, but is potentially very useful. City centre operation, which tends to increase dose rate, is associated with low exhaust gas temperatures, where it is difficult to achieve regeneration in the DPF. Under these circumstances, a higher FBC concentration in the fuel is a positive advantage.

Conversely, where a vehicle is operated for long periods at comparatively high speed and power output, exhaust temperatures will be much higher. Under these circumstances, DPF regeneration is readily achieved, and may in fact be continuous. Thus the effective reduction in dose rate resulting from the timer based dosing system is not a problem, and helps to reduce overall use of the FBC.

A timer based system was constructed and installed on the engine test bed, with engine A, using the same fuelling arrangements as previously described, except that the turbine fuel flow measurement unit was removed. FBC dose rate was set for a fixed treat rate of 34mg/hr. This dose rate was calculated for a fuel flow rate intermediate between the injection pump idle flow of 19kg/hr and the peak pump delivery of 60kg/hr. The same FBC dosing rate was used for all test conditions.

The computer model developed earlier to calculate the effect of the in-line FBC dosing system on average metal content over time was modified to allow it to predict fuel metal content assuming time based dosing. Two engine operating conditions were assumed, i.e. 1260rev/min, 5Nm and 2710rev/min, 30Nm, and the model run to simulate 200 hours of engine operation. A run of this duration naturally included refuelling events. The results of the model runs are shown in Figure 10 for the 1260rev/min, 5Nm speed/load condition.

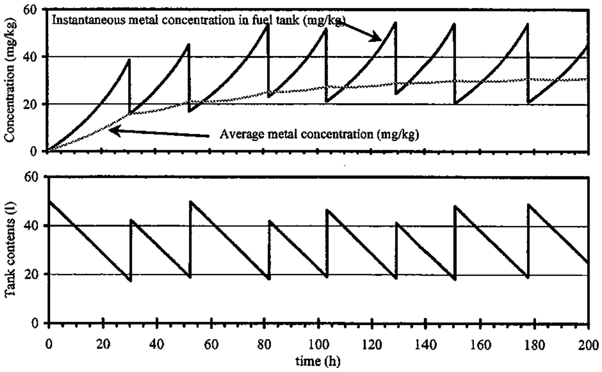


Figure 10. Computed fuel metal content changes for 1260rev/min, 5Nm : 34mg/hr FBC dose rate

The computer model was also run for the higher speed condition using the same 34mg/hr FBC dose rate; results are shown in Figure 11. The computed average metal concentration over time is shown for both operating conditions, in the upper panels of Figures 10 and 11 respectively. In Figure 10, the computed average fuel metal content is observed to stabilise at about 30mg/kg after about 140hours of operation. In Figure 11 the computed stable average fuel metal content reaches a level of 7mg/kg after about 80 hours of operation. These differences are significant, since Figure 10 depicts an engine operating condition of indefinite idle conditions (1260 rev/min, 5Nm), while Figure 11 depicts close to highway operation (2710rev/min, 30Nm).

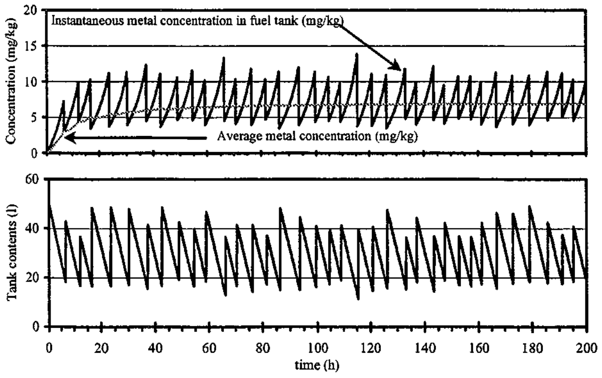


Figure 11. Computed fuel metal content for 2710rev/min, 30Nm : 34mg/hr FBC dose rate.

In reality, engine load would be higher for real road operation, which would decrease effective mean metal content in the fuel. However, these computed results depict the essential characteristics of FBC time based dosing, i.e. higher metal content under low duty conditions and lower metal content under higher duty conditions. It was believed that this would be precisely what is required for FBC-DPF technology in real vehicles. Engine tests provided interesting regeneration data as shown in Figures 12 and 13, below.

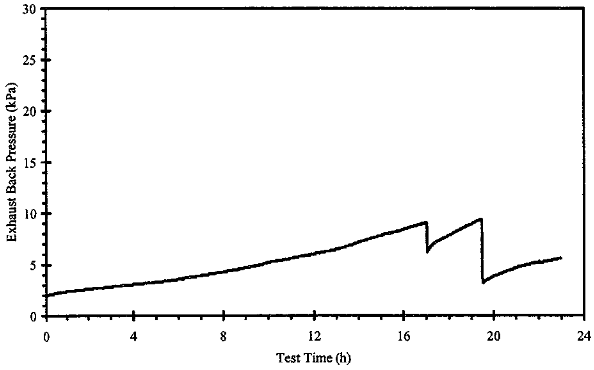


Figure 12. DPF pressure trace for 1260rev/min, 5Nm: fixed 34mg/hr FBC dose rate

Figure 12 shows a long build up to the first regeneration followed by more frequent regenerations as fuel metal content increased. Fuel metal content had reached about 16-17mg/kg at the first regeneration. Results obtained with the time-based system were slightly different from the results with the flow-based system, shown in Figure 6 (regeneration first occurred after about 12 hours, when metal content was about 24mg/kg)

These differences probably stem from the different settings of the dosing system employed for the two test runs. In practice, these differences produced different levels of soot accumulation, and different times of first regeneration. In the first run, back pressure at first regeneration was 8kPa, compared with about 10kPa after 16-20 hours in the later run, indicating a higher soot burden in this test. Thus although metal content was still relatively low, at 16-17mg/kg, the combination of soot accumulation and soot metal content produced regeneration. Conversely, in the first run, the higher dosing rate caused regeneration at lower back pressure because of the higher fuel metal content. However, it must be accepted that stochastic DPF regeneration is a process subject to wide variation, and that a high level of repeatability may not result from repeated tests.

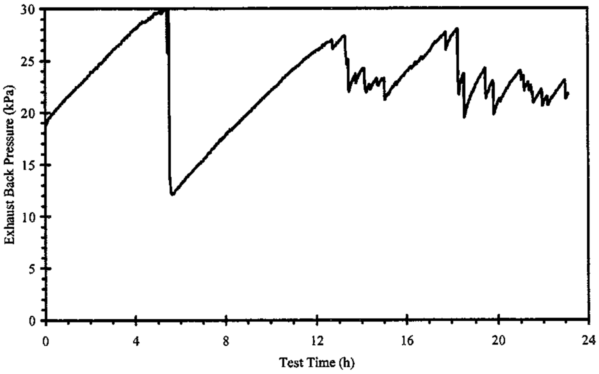


Figure 13. DPF pressure trace for 2710rev/min, 30Nm: fixed 34mg/hr FBC dose rate.

Figure 13 shows a similar picture of relatively slow initial regeneration activity, with more frequent regenerations later after fuel metal content had increased. Despite the low average fuel metal content of about 6-7mg/kg, the relatively high exhaust temperature of about 300°C recorded during the engine tests allowed regenerations to occur stochastically.

The results shown in Figures 12 and 13 were very encouraging. It was decided to take the next step, which was to fit the in-line dosing system to a road vehicle fitted with a passive DPF system.

ROAD VEHICLE TESTING

LONDON TAXIS

During the second half of 2001, and the first half of 2002 a comprehensive demonstration programme had been taking place with London 'Black Cab' taxis. The contribution of these diesel powered vehicles to air pollution in London has become the subject of much discussion in recent times. Octel were involved in a UK government assisted programme to demonstrate the potential air quality benefits of fitting DPF systems to black cabs in London. This work has been extensively reported recently (7,8). The taxis were powered by engines of type B, details of which are provided in Table 1. Silicon carbide DPFs were used, details of which are given in Table 2. Taxis were operated on commercially available diesel fuel. Properties are believed to be similar to the test fuel ULSD 3, summarised in Table 3.

Difficulties were experienced with the first taxi operated, as a result of the mal-function of the FBC dosing system. The dosing system functioned by detecting a refuelling event, following which a calculated dose of FBC was added in one batch over a few seconds, by means of an electrical pump. Problems were encountered because surges in tank fuel level were interpreted as refuelling. This led to excessive FBC content in the fuel caused by multiple dosing.

It was decided early in 2002 to fit another of the taxis in the programme with an in-line system, in place of the batch dosing system originally fitted. A development in-line dosing system had just completed engine testing, so a pre-production unit was assembled and installed on a black cab for use in London. The system was set up using time-based dosing. The solenoid pump was set to operate once every 190 seconds. The vehicle was already equipped with data-logging equipment, so it was possible to check on the frequency of regeneration and the level of exhaust back pressures. A trace from the vehicle is shown in Figure 14.

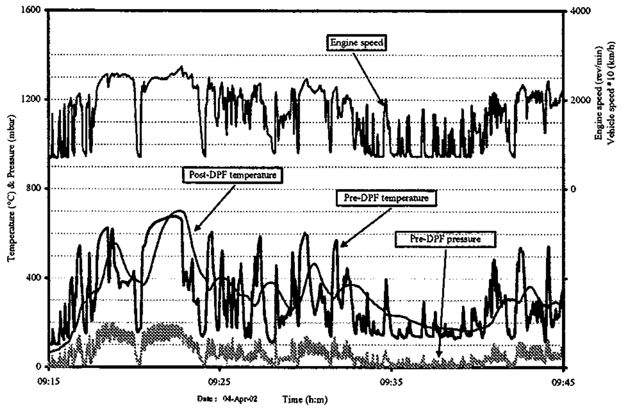


Figure 14. DPF data logger trace of taxi with in-line dosing system.

Figure 14 shows engine speed data on the upper trace, with DPF upstream and downstream temperatures on the middle two traces. Pressure immediately upstream of the DPF is shown on the bottom trace. The variability of duty cycle in a city environment is clearly shown, with some periods of several minutes at engine speeds of 2000-2500rev/min interspersed with periods of prolonged idling and short acceleration/deceleration cycles. During acceleration, exhaust gas temperature rose briefly to quite satisfactory levels, i.e. above 400°C, even exceeding 600°C for a period of about 20 seconds.

The trace shows that the FBC system is able to use these brief excursions, or spikes of temperature, to secure regeneration. The downstream temperature trace clearly shows an exotherm from burning soot, at about 9.23-9.24am (time shown on the x-axis), accompanied by falling DPF pressure. The combination of an exotherm and falling DPF pressure is characteristic of the regeneration event. DPF pressures later in the trace, at 9.42-9.45am show reduced DPF pressures, compared with pre-burn out operation, even though engine speeds again reach 2000rev/min for 2 or 3 minutes.

The system was also fitted to two other London black cabs, with similarly satisfactory results. The exhaust back pressure data from one of these taxis was normalised using the following formula: -

$P_{norm} = (P * N_{idle}) / (P_{idle} * N)$

Where P is the measured pre-DPF pressure, P_{idle} is the value of P at idle with a clean DPF and N is the measured engine speed, and N_{idle} is the engine idle speed. A rolling average of the normalised data has been plotted over a 3000 km period with the taxi running on batch treated fuel. A similar rolling average for operation with the novel in-line dosing system is shown for comparison.

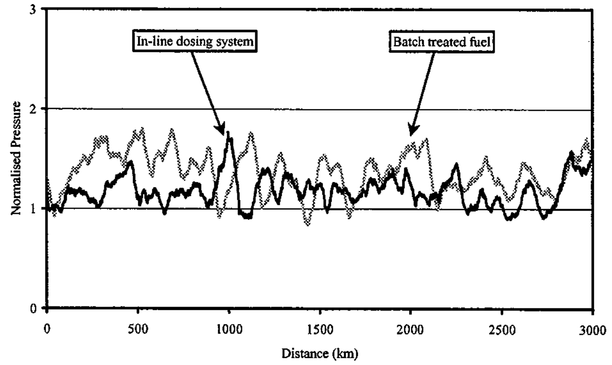


Figure 15. Pre-DPF pressure data from taxi using batch dosing versus in-line dosing

The DPF pressure shown in Figure 15 has been normalised for idle speed and at elevated engine speeds using the formula:-

$P_{norm} = (P^* N_{idle}) / (P_{idle}{}^* N)$ described in more detail above.

From Figure 15 it can be seen that the normalised pressure trace recorded with the in-line dosing system compares favourably with that obtained with the batch dosing system, over 3000km. This result was regarded as a useful demonstration of the in-line dosing system. The use of a passive DPF system in perhaps one of the most demanding environments likely to be encountered, i.e. on a taxi operating in central London, was strong evidence of the soundness of the original thesis behind the in-line dosing system operation. Reliance was placed purely on the use of FBC to secure regeneration. The decision was taken to consolidate earlier patent activity, and to produce the dosing system commercially.

Although the system was conceived for use with retrofit DPF applications, there is no reason in principle why this system should not be used as original equipment on new vehicles. In addition to the virtues of simplicity, leading to low first cost, and improved reliability, the system offers potential to supply information useful for on-board diagnostic requirements. Also, there is potential to operate the system in closed loop mode by linking FBC treat rate to DPF back pressure. It has been shown that higher fuel metal contents encourage regeneration, so in principle the system offers the potential to increase the rate of FBC dosing as pre-DPF back pressure increases. Once regeneration has been achieved, dosing frequency would return to the normal set point level. This concept could be extended to make the rate of FBC dosing entirely dependent on soot accumulation, linked to back pressure. This cannot be easily achieved with a batch dosing system. The use of this type of in-line system is not restricted to the FBC tested. In could in principle be applied to any FBC chemistry.

FIRE APPLIANCE SUPPORT VEHICLE

The in-line dosing system was also applied to a very different test vehicle in a trial carried out in collaboration with Greater Manchester (GM) Fire Service. A hose laying and collection vehicle used for driver training was selected for application, as this particular vehicle had been shown to experience a duty cycle giving very low exhaust temperatures. The mode of operation, with long periods of idling and slow running during hose collection operations, made fitting a DPF to this vehicle very challenging. The proposal was to use a passive DPF, ie without auxiliary heating or a control system, again relying on the catalytic effect of the FBC for regeneration, as for the taxis. The size of the truck, which was powered by a 6 litre turbocharged diesel engine, also represented a considerable difference from the London taxi applications.

The fire support vehicle was powered by an engine of type C, details of which are provided in Table 1. A silicon carbide DPF was used, details of which are given in Table 2. The vehicle was operated on commercially available diesel fuel. Properties are believed to be similar to the test fuel ULSD 3, summarised in Table 3.

The GM fire training vehicle was fitted with a DPF, and the novel FBC in-line dosing system in the spring of 2002. The dosing solenoid pump and electronic control dosing components used were the same as for the taxis, although a larger FBC storage container was fitted to the fire appliance. The only significant difference lay in the frequency of dosing, ie the rate at which the solenoid pump operated. The dosing system was set to pulse at a fixed frequency independent of the instantaneous flow of fuel to the injection pump, as for the London taxi applications. Dose rate was adjusted to allow for the heavier fuel consumption of the truck. A data logger recording DPF pressures, and upstream and downstream temperatures, was also fitted. The vehicle was operated for about 4 months to check system operation, which appeared to be satisfactory.

Figure 16 shows a trace indicating an exotherm from regeneration. The downstream temperature has risen above the temperature upstream of the DPF as a result of soot burn-out in the DPF. The very low DPF inlet temperature, in the range 180°C to 200°C is evident from Figure 16. The temperature range is characteristic of the operation of this particular vehicle.

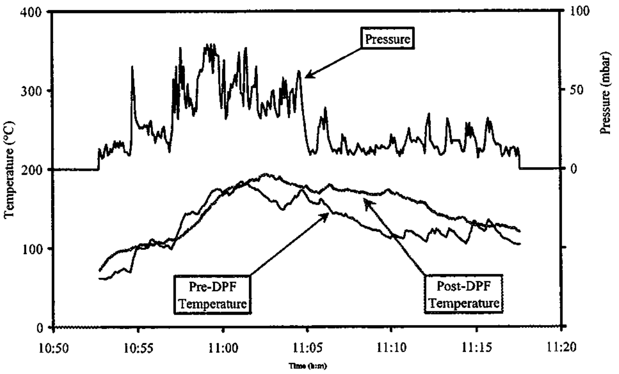


Figure 16. Regeneration on G. M. fire appliance vehicle

This range of temperature is far below the level encountered in the majority of cases of vehicle operation where a DPF is fitted. It would normally be expected that regeneration would stem from some period of operation at temperatures above 350-400 ° C, as observed in the London taxis. However, the duty cycle of this particular vehicle is such that these temperatures are almost never experienced. The feasibility of achieving regeneration at all might therefore be questioned.

Examination of the trace in Figure 16 shows that, despite the low temperatures, post DPF temperature rises above the inlet temperature at about 11.01am on the time chart, and remains above the inlet temperature until about 11.15am. The back pressure trace shows a pressure reduction at about 11.05am. This is about 4 minutes after the onset of downstream temperature increase above the inlet temperature, a physical state which then continues for a further 10 minutes, although the engine is clearly idling or otherwise operating at very low load and speed.

The increase of DPF outlet temperatures above inlet temperatures can result from the thermal inertia of the ceramic element storing heat from the exhaust gases. Although examples of thermal inertia in the ceramic DPF element have been seen on data logger traces, it is not believed that this is the explanation here, because the duration of elevated temperatures is far longer than would normally be associated with thermal inertia effects. Figure 17 shows a trace from the same vehicle where outlet temperatures higher than inlet temperatures are seen for about 5 minutes. It is believed that this effect is due solely to thermal inertia in the DPF.

In the case of the trace shown in Figure 16, what is believed to be happening is relatively slow burning of soot within the DPF. Because of the low temperatures, the rate of combustion is much slower than would be experienced at a more typical regeneration on-set temperature above 400 ° C for example. At this sort of temperature, complete burn-out in 1-2 minutes is normal with iron-strontium FBC regenerations (3).

Support for the view that regeneration is possible below 200 ° C can be found in test bed DPF work reported earlier (9). In this work, a bed engine was operated continuously for 14hours at 1260rev/min and 5Nm, ie close to idle conditions. DPF inlet temperatures lay between about 120 ° C and 130 ° C, yet six stochastic regeneration events were recorded, through the process of soot accumulation and burn-out, with exotherms clearly evident on the trace.

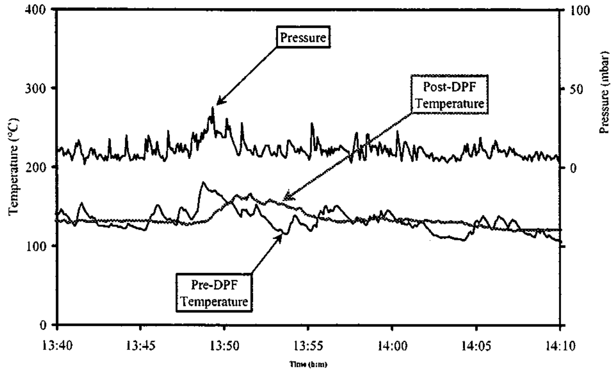


Figure 17. Thermal inertia effects in the DPF.

The possibility of achieving regeneration at temperatures so far below normal carbon burn-out point has been explained in terms of hydrocarbon-driven combustion, where the hydrocarbons are attached to the dry solid particulate material in the form of high SOF fraction (10). This sort of regeneration behaviour is rarely seen in road vehicles, because duty cycles in which exhaust temperatures are consistently so low are uncommon. Normal operating speed and load conditions force exhaust temperatures to exceed these low values. The lowest previously recorded temperature of regeneration with iron-strontium FBC was seen with a passenger car in which regeneration was clearly evident at an inlet temperature between 220 ° C and 225 ° C (3).

In the case of the GM fire appliance, it is believed that slow regeneration is evident, as depicted in Figure 16, despite the low exhaust temperatures. This view has credibility, in addition to the data logger evidence, because of the length of time for which the vehicle has been operating without obvious soot clogging problems. It seems likely that episodes of high fuel metal content produced by the in-line dosing system, as a result of low fuel tank levels, may be encouraging regeneration at these extremely low DPF temperatures.

CONCLUSIONS

1. A fuel borne catalyst dosing system was developed around a solenoid operated pump, in order to add a defined quantity of an organo-metallic additive to diesel fuel. The system design was simplified compared to batch-mode designs which function in response to the refilling of the vehicle fuel tank. The design employed doses FBC directly into the fuel line feeding the engine injection pump. Initial in-line system designs dosed in proportion to fuel flowing to the injection pump.

2. Computer modelling confirmed that fuel metal content would vary in a non-linear relationship with fuel tank volume, because of the high return flows from the injection pump to the fuel tank. This arrangement produces significant multiple dosing of fuel with FBC.

3. Engine testing showed that despite the non-linear fuel metal concentration resulting from the use of the in-line dosing system, the time-averaging effect on the metal content of soot accumulated within the DPF allowed stochastic regeneration, or burn-out of the soot, within the DPF.

4. The system was further simplified by adopting constant time-based FBC dose rates. This approach increased fuel metal content for low speed operation and reduced fuel metal content for high speed and load operation. Engine testing with widely different speed and load conditions, operating with the same constant mg/hr FBC dose rate, showed that stochastic regeneration in the passive DPF was achieved at both operating conditions.

5. The in-line dosing system was applied to road vehicles to assess performance under actual driving conditions. Vehicles tested ranged from London black taxis to a heavy duty fire appliance training vehicle used for low duty cycle operations. Data logger traces indicated that DPF regeneration with passive filter units was taking place. London taxis covered distances ranging from 12,000 to 20,000km.

6. Although the system was tested with retrofit DPF applications, it could be used as original equipment on new vehicles. Simplicity, leading to low first cost, and improved reliability, is allied to capability to supply information useful for on-board diagnostic requirements. Also, there is potential to operate the system in closed loop mode by linking FBC treat rate to DPF back pressure. The use of the system is not restricted to the FBC tested, but could be extended to any FBC.

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