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Low Power Autoselective Regeneration of Monolithic Wall Flow Diesel Particulate Filters

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ABSTRACT

This paper presents research into a novel autoselective electric discharge method for regenerating monolithic wall flow diesel particulate filters using low power over the entire range of temperatures and oxygen concentrations experienced within the exhaust systems of modern diesel engines. The ability to regenerate the filter independently of exhaust gas temperature and composition significantly reduces system complexity compared to other systems. In addition, the system does not require catalyst loading and uses only mass-produced electronic and electrical components, thus reducing the cost of the after-treatment package.

Purpose built exhaust gas simulation test rigs were used to evaluate, develop and optimise the autoselective regeneration system. On-engine testing demonstrated the performance of the autoselective regeneration process under real engine conditions. Typical regeneration performance is presented and discussed with the aid of visual observations, particulate mass measurements, back pressure measurements and energy consumption. The research demonstrates the potential of the novel autoselective method for diesel particulate filter regeneration. The autoselective process does not require an exhaust by-pass and enables the system to be low power, catalyst-free and exhaust temperature independent.

INTRODUCTION

Internal combustion engines are expected to remain a significant technology for transportation well into the mid 21st century^[1]. The torque characteristics, combustion robustness, thermal efficiency and large practical bore size of diesel engines make them widely used for on-highway, off-highway, marine transport and power generation applications. Development of emission

legislation around the world has driven reductions in particulate matter (PM) and NO_x emissions to levels that require engine exhaust aftertreatment. Future legislation such as EURO VI is likely to force all diesel engines to use PM exhaust emission aftertreatment systems and it is foreseeable that gasoline engines might need similar technologies.

The most promising engine exhaust PM reduction technologies are based around diesel particulate filters (DPFs), most commonly monolithic wall flow DPFs^[e.g. 2]. Monolithic wall flow DPFs are capable of filtering >95% of the particulate matter emissions from diesel engines^[3], including nano-particles. Alternative filter substrates such as ceramic foams (~80% filtration efficiency^[e.g. 4]) and partial filters (~50% filtration efficiency^[5]) are of less interest for new engines due to their lower filtration efficiency but can be effective in retro-fit applications^[5].

As the PM loading on the filter increases the resistance to exhaust gas flow increases resulting in an increased pressure drop across the filter. This increasing engine back pressure reduces engine power and increases fuel consumption. To maintain acceptable exhaust system back pressure the filter needs periodic cleaning (regeneration) to remove the trapped particulate matter. Up to now this has only been achieved in production engines by oxidizing the trapped PM although some research continues into non-oxidative methods. The focus of this paper is on a novel oxidative regeneration system that overcomes many of the disadvantages of existing regeneration technologies.

DPF regeneration strategies can be grouped generally into 3 categories:

1. Thermally enabled (e.g. burners^[6])
2. Catalyst enabled^[e.g. 7] (including low temperature plasma systems^[8])
3. Non-oxidative methods (e.g. reverse flow^[9])

Thermal regeneration processes increase the PM temperature to typically $>550^{\circ}\text{C}$ at which, with careful control of gas flow produces a self-sustained oxidation reaction that can regenerate the filter in ~ 3 minutes. This has been achieved in the past using microwaves^[10] (for direct coupling of thermal energy to the PM), electrical heating^[11] and diesel fuel burners^[6] in the exhaust system. These systems typically rely on close control of gas flow rate, temperature and PM loadings which make them challenging to implement. Thermal runaway can often lead to melting and cracking damage of the filter substrate^[12] and has in many cases demanded more robust, and expensive, silicon carbide DPFs.

Catalyst enabled regeneration typically uses either fuel doping^[13] or a wash coat on the substrate^[7] to reduce the temperature at which rapid oxidation of the PM occurs. This allows regeneration at lower exhaust gas temperatures and uses less energy to actively regenerate. However, these systems usually require expensive catalyst materials such as platinum. Upstream oxidation catalysts have also been used with fuel sprays to increase the exhaust gas temperature^[14]. Problems achieving reliable regeneration temperatures are often encountered with the low exhaust gas temperature of modern diesel engines. The chemical properties of electrical plasmas have been used to promote oxidation of the trapped PM using both in-situ and upstream non-thermal plasmas^[8]. These plasma systems are still very sensitive to exhaust gas temperatures and many require significant amounts of electrical power^[15].

Oxidation catalysts have also been implemented upstream of the DPF to convert engine out NO into NO_2 which is effective at oxidising PM at relatively low temperatures^[16]. Such systems have seen wide use, especially in the retro-fit DPF market. However, for satisfactory operation it requires a minimum NO_x/PM ratio, low sulphur fuel as well as minimum exhaust temperatures which cannot always be guaranteed.

Non-thermal regeneration technologies such as reverse flow systems^[9] struggle to effectively regenerate the entire filter volume and use bulky high pressure devices to separate the PM from the filter surface. Difficulties with PM disposal remain after regeneration.

An ideal DPF regeneration system would be robust, reliable, compact, would not require precious metal catalysts, be low cost, low energy, have low electrical power demand and be capable of operating under all typical engine exhaust conditions. This paper presents for the first time research into a novel plasma based oxidative DPF regeneration system that performs well on all of these criteria and is considered to have significant potential as a key part of next generation engine exhaust aftertreatment systems.

AUTOSELECTIVE REGENERATION OF DPFs

The autoselective DPF regeneration system uses a glow discharge plasma (an example of which is shown in Figure 1) to oxidize the trapped particulate matter. This system uses the localised heating effect of an electrical plasma to increase the local PM temperature to cause rapid local PM oxidation, unlike many other plasma processes which treat all the exhaust gas. The autoselective discharge reaches temperatures of $>1000\text{ K}$ in $<10\text{ ms}$ and the PM is heated in a similar time. The direct conversion of electrical to thermal energy in the plasma results in focused high temperature regions for regeneration using very low electrical powers ($<20\text{ W}$). As well as heating, the PM oxidation reaction is promoted by the active species (e.g. ozone) generated within the plasma column.

Figure 1 Photograph of a typical autoselective glow discharge plasma

A key feature of the electrical plasma used is its autoselective nature. This means that the electrical plasma self-selects PM and once one region has been cleaned, it will move to other regions of the filter that have larger amounts of trapped PM. This effect is a result of the increase in the local electric field strength caused by the conductive PM which acts as an electrode and attracts the discharge. This effect can be very significant where the autoselective discharge selects only the PM cake layer and progressively cleans the filter surface.

Using an arrangement shown in Figure 2, the PM is effectively oxidised. The discharge is formed between a high voltage external pin electrode and travels to the PM cake layer on the filter. This is grounded through the canister and engine exhaust system. The local high temperatures only exist in the immediate region of the PM and the PM cake layer is therefore oxidised. Sectioned examples of wall flow diesel particulate filters are shown in Figure 3 before and after-treatment with an $\sim 20\text{ W}$ autoselective discharge. The autoselective discharge successfully oxidised the PM cake layer that was trapped on the DPF. Visual inspection showed that some of the depth bed filtered PM remained. This has advantages for post regeneration filtration efficiency since the filter will more rapidly reach the cake filtration mode (i.e. exhibits maximum filtration efficiency under these test conditions). Effective low power regeneration with this external pin electrode arrangement is limited to the first $\sim 25\text{ mm}$ of the DPF.

Figure 2 Schematic of autoselective regeneration applied to a WFF with a 'pin' electrode

Figure 3 Cross section of (a) an untreated PM loaded DPF and (b) a PM loaded DPF regenerated by the autoselective discharge.

However, to regenerate within the entire filter volume the electrical plasma was generated between two parallel electrodes inserted in the filter channels, shown in Figure 4. In this case, the plasma travels in a radial direction within the filter rather than axially. This retains the autoselective nature of the discharge and allows the plasma to reach the entire filter volume. The effect of inserting the required number of electrodes on the filter back pressure was negligible. The autoselective regeneration is intended to be a continuous regeneration process during engine operation with it self-selecting the regions of the filter containing the most PM.

Figure 4 Schematic of the cross section of an inserted electrode arrangement

A significant advantage of the autoselective system is its ability to be scaled in size to match any given application. A single autoselective discharge is typically capable of regenerating trapped PM at a rate of $0.15\text{--}0.6 \text{ g h}^{-1}$ when using an external electrode and $0.1\text{--}0.2 \text{ g h}^{-1}$ with the inserted electrodes. Typical engine-out PM is higher than this, therefore, multiple autoselective discharges were

used. The system is scalable such that the number of plasmas are matched to specific applications to obtain required regeneration rates within given electrical power limits.

Another advantage is that this system does not have any moving parts (e.g. valves) that will wear and deteriorate. The durability, therefore, is expected to be good however at this stage, no durability testing has been completed to confirm this.

EXPERIMENTAL METHODS

This section describes the experimental methods employed during the research including the main hardware, measurement methods and purpose-built rigs. These methods were used for the work described in this paper.

POWER SUPPLY

The autoselective discharge is generated by using a high voltage resonant transformer. The main components are shown in Figure 5 and are all standard electronic and electrical components that are currently produced in high volume and, therefore, already low cost. A variable voltage square wave input (typically $\sim 180 \text{ V}$ peak-peak) to the primary causes resonance of the transformer. The use of a resonating transformer circuit provides a high open circuit voltage with no load to breakdown the region between the electrodes. When the gap between the electrodes is broken down the resonance is heavily damped and the output voltage drops enabling the plasma to be stabilised without additional components and, therefore, the power supply to be more compact. The current in the high voltage secondary can be controlled by varying the primary voltage.

Figure 5 Schematic of the power supply components

REGENERATION PERFORMANCE MEASURES

The regeneration performance was evaluated by considering three important factors:

1. Regeneration rate
2. Regeneration effectiveness (i.e. regeneration rate per unit power)
3. Regeneration distribution.

Regeneration rate, R , is calculated based on the mass of PM removed from the filter in a given duration, typically

expressed in units of g h^{-1} . This gives an average regeneration rate for the whole test duration as

$$R = \frac{\Delta m}{t} \quad (1)$$

where Δm is the removed filter mass over a duration t . Regeneration effectiveness, r , is an indication of how much energy is required to remove PM at a given rate. It is calculated as

$$r = \frac{R}{P} = \frac{\Delta m}{Pt} \quad (2)$$

where P is the electrical power demand during regeneration.

Regeneration distribution is a qualitative measure that evaluates how uniform the regeneration is, typically with the flow mapping procedure that is described later.

Pre and post weighing

A typical 5.66 inch (144 mm) diameter wall flow DPF has a mass of ~ 1.3 kg. Trapped PM quantities during regeneration vary typically between 1 g litre^{-1} and 10 g litre^{-1} ($\sim 2.5 \text{ g}$ and $\sim 25 \text{ g}$ respectively). Mass measurements of changes of $<1\%$ of the total filter mass require careful environmental considerations. Volatile PM components and atmospheric moisture content can affect mass measurement and often lead to measurements at elevated temperatures. Pre-heating of the sample was inappropriate for this research since the volatile components of the PM could have a significant impact on the electrical characteristics of the cake layer, and hence the regeneration characteristics. To ensure the same behaviour that would occur in practice the tests were carried out without preheating the filter samples. Where the filter was weighed at elevated temperatures after loading on an engine, buoyancy effects on the mass measurements were taken into account^[17].

Mass measurements were made to a resolution of 0.01 g using an analytical balance prior to loading the filter, after loading the filter ('pre-weight') and after regenerating the filter ('post-weight'). A minimum of three measurements were taken for each data point.

Electrical measurements

Power consumption measurements were made at the electrodes and at the main power supply. The voltage was measured at the electrodes using a Tektronix P6015 1000:1 high voltage probe and the current measured with a Pearson 2877 1:1 high frequency current transformer probe. The cyclic integral of the instantaneous calculated power over multiple cycles was used to calculate the average power consumed at the electrode. A power meter was used to record the average power from the mains supply.

Flow mapping

Comparative measurements of the regeneration within individual channels was made by insertion of a probe designed to measure a flow pressure at a channel outlet. This is shown in Figure 6. With a low flow rate through the whole filter, the probe was moved to each channel outlet. The effect of the probe on the flow resistance and flow rate through the test channel prohibited quantitative flow rate measurements but allowed qualitative comparisons of the channel flow rates, and hence levels of regeneration. The more regeneration that had taken place, the higher the flow rate through that particular channel and the higher the pressure.

Figure 6 Schematic showing the flow mapping method

HOT FLOW RIG

Extensive experimental testing was carried out on a purpose built engine exhaust simulation rig designed to generate gas flow rates of up to 400 kg h^{-1} at temperatures of up to 550°C . The main components are shown in Figure 7. The hot flow rig consisted of a 7.5 kW centrifugal blower, a bypass arrangement to limit the workload of the blower, a 36 kW electrical heater, an insertion point, optical access and filter housing. The insertion point could be used for dilution (with N_2 or CO_2) and to increase humidity to better simulate real engine exhaust conditions.

Filter loading requirements

Testing of the regeneration system on the hot flow rig required pre-loading of the DPFs with PM. The PM properties vary with engine speed and load and representative PM properties were needed for testing. The density of the PM layer, ρ_{PM} , is a function of the size and morphology, i.e.

$$\rho_{PM} \propto d_b^{d_r-3} \quad (3)$$

where d_b is the mobility diameter of the PM and d_r is the fractal dimension of the agglomerate^[18]. Assuming a solid material density the same as carbon of 2270 kg m^{-3} , an average spherule diameter of $0.3 \mu\text{m}$ and fitting the fractal dimension as a function of load to data presented in^[19], the PM density can be approximated as

$$\rho_{PM} = 2700 \times 300^{-(0.185+0.0201P_{BMEP})} \quad (4)$$

where P_{BMEP} is the brake mean effective pressure of the cycle. Applying this relationship to typical heavy duty diesel engine drive cycles results in an average PM density between 116 and 177 kg m⁻³. A steady-state engine load that will approximate the same average density is between 58 and 74% full load. The pre-loading of filters was carried out within this engine load range for all tests. Analysis of the PM composition using data from [20] resulted in similar representative engine loads. For consistency, pre-loading of filters with PM was carried out at 1400 rpm.

Figure 7 Schematic of the hot flow rig simulating diesel engine exhaust gas

ENGINE TEST RIG

The engine testing and filter pre-loading was carried out on a Perkins 1100 series 4 cylinder, turbocharged, charge cooled heavy duty diesel engine with a canister similar to that used on the hot flow rig. The engine was warmed up while bypassing the filter canister. Once warm the exhaust gas was directed through the filter and canister for the test. Downstream of the filter was a transparent machined borosilicate plate that allowed optical access and high voltage electrode feedthrough to the filter. Upstream of the filter was a fused silica window for optical access to the upstream face of the filter. Estimations of PM loading rates were made using an AVL415 smokemeter with correlations validated in-house by pre- and post-weighing of filter samples.

REGENERATION CHARACTERISTICS

Autoselective regeneration uses the thermal properties of the autoselective discharge to oxidize the PM trapped on the DPF surface. This has been verified by comparing the oxidation rate of PM exposed to the same amount of heating from a 532 nm laser (i.e. heating without the chemical effects of the plasma). The autoselective discharge in contact with the PM cake layer causes rapid oxidation of the PM without direct contact between the plasma and ceramic surface, however, the regeneration is limited to near ~25 mm radius of the electrode. To regenerate the entire filter volume electrodes were inserted into the channels to generate a radial autoselective discharge within the filter volume. The effect of inserting the electrodes into the filter volume are discussed later in this paper.

There are many types of plasma that can be formed with the described electrode arrangement such as dielectric barrier discharges (DBDs), corona discharges, glow discharges and arc discharges. Arc discharges were considered unsuitable due to the thermal damage they would cause to the filter substrate. The regeneration performance of DBD, corona and glow discharges were investigated with the results shown in Table 1. The regeneration performance of the plasma is closely related to the thermodynamic temperature of the plasma. In the electrode configuration used the filamentary discharges have a relatively low thermodynamic temperature (close to ambient temperatures) which is reflected in the low regeneration rate and regeneration efficiency. Glow discharges can have thermodynamic temperatures (i.e. ion temperatures) >1000 K and can, therefore, rapidly oxidize the trapped PM.

Table 1 Comparison of the regeneration performance of different types of electrical plasma

Discharge Type	Typical Rate g h ⁻¹	Typical Effectiveness g h ⁻¹ kW ⁻¹
Glow	0.55	39.5
Corona	0.07	9.1
DBD	0.01	0.2

Environmental Effects

Design of Experiments (DoE) methods were used to investigate the effect of exhaust gas flow rate, exhaust gas temperature, oxygen concentration and humidity on regeneration rate and discharge power consumption using the hot flow rig described earlier with a 2.4 litre 100 cells per square inch (~15.5 cells cm⁻²) WFF. The filter and electrode arrangement were as described in Figure 2. The power consumed by the discharge was not significantly affected by these variables.

The effect of exhaust gas temperature on the regeneration rate is shown in Figure 8. As the exhaust gas temperature increases the regeneration rate increases. This is related to the reduced thermal energy

input required to rapidly oxidize the PM. Since the plasma self selects locations with high amounts of PM, the regeneration rate increases accordingly.

Figure 8 Effect of exhaust gas temperature on regeneration rate

Figure 9 shows that at higher exhaust gas flow rates the regeneration rate is reduced. This is a result of the cooling effect of the flow rate on the autoselective discharge and the heated PM which reduces the heating effect of the plasma. The drop in regeneration efficiency ($\sim 15\%$ between $100 \text{ m}^3 \text{ h}^{-1}$ and $250 \text{ m}^3 \text{ h}^{-1}$) is small enough that the regeneration effectiveness (based on the power at the electrodes) was still $>30 \text{ g h}^{-1} \text{ kW}^{-1}$ (equivalent to $<167 \text{ W}$ for 5 g h^{-1} regeneration rate).

Figure 9 Effect of gas flow rate on regeneration rate ($100 \text{ m}^3 \text{ h}^{-1}$ corresponds to space velocity of $\sim 40000 \text{ h}^{-1}$)

Figures 10 and 11 show the effect of gas humidity and oxygen concentration respectively on the regeneration rate. It shows that the autoselective discharge is capable of effectively oxidizing trapped PM under all anticipated oxygen concentrations and humidities typical of diesel IC engines.

The results showed that the autoselective regeneration system can operate independently of the engine operating conditions. Although the regeneration rate and the regeneration effectiveness were affected by gas flow rate and temperature, they were still very competitive.

Figure 12 shows the effect of frequency and discharge current on the regeneration rate of a glow discharge in contact with a PM cake surface. It is clear that the

frequency has little effect on the regeneration rate. Regeneration rate increases with increasing discharge current as the temperature of the plasma, and therefore heating of the PM, increases.

Figure 10 Effect of water vapour concentration on regeneration rate

Figure 11 Effect of oxygen concentration on regeneration rate

Figure 12 Effect of discharge current and frequency on regeneration rate

Increasing current reduces regeneration effectiveness. Within the error bands of the experiment, frequency has a negligible effect. Implementation of the autoselective regeneration system, therefore, can be optimised for specific applications by optimising the regeneration effectiveness (i.e. power consumption) with regeneration rate. The relationship between regeneration rate and regeneration effectiveness for changing current is shown in Figure 13.

Figure 13 Effect of discharge current on regeneration effectiveness

The heat flow to the PM and the substrate can be controlled by cyclically switching the plasma on and off. The effect of the switching the plasma on the regeneration performance was investigated. Figure 14 and Figure 15 show the effect of duty cycle and period on the regeneration rate where the duty cycle and period are that of the switching of the plasma. The effect was predictable as proportional to the duration for which the plasma was applied. This shows that the intermittent application of the autoselective discharge can be used to optimise the filter material thermal loading relatively independently of regeneration performance.

Figure 14 Effect of duty cycle of the plasma switching on the regeneration rate

Figure 15 Effect of the period of the plasma switching on the regeneration rate

IMPLEMENTATION WITH A MONOLITHIC WFF

The insertion of electrodes into the filter channels makes a fundamental difference to the autoselective discharge as it now travels through the wall, and hence heats the ceramic substrate as well as the PM. Ceramic material temperatures limit the amount of heating that can be achieved resulting in, typically, a regeneration effectiveness of $\sim 20 \text{ g h}^{-1} \text{ kW}^{-1}$ (equivalent of $\sim 250 \text{ W}$ to regenerate $5 \text{ g h}^{-1} \text{ PM}$).

Studies of the factors affecting regeneration performance showed similar results to those presented earlier. In addition, the effect of PM loading between 2 and 4 g litre^{-1} on regeneration rate is shown in Figure 16. Increasing PM loading tended to increase the regeneration rate. This can be explained by considering the nature of the regeneration. The autoselective discharge can regenerate a region where it attaches to conducting PM. If there is more PM in this region, the regeneration rate will increase accordingly. Promisingly, the regeneration system is capable of working at low PM loadings as well as very high PM loadings. In the example presented a switch of plasma type at very low loadings ($<0.5 \text{ g litre}^{-1}$) from a glow discharge to a filamentary discharge was observed. This led to a subsequent drop in regeneration performance like that shown earlier in, e.g. DBD in Table 1. The plasma alternated between the high performance glow discharge and low performance filamentary discharge with PM loadings between 0.5 and 1.8 g litre^{-1} for a peak to peak voltage of 12 kV .

Figure 16 Effect of PM loading on regeneration rate

To regenerate the entire filter volume and achieve the required overall regeneration rate, it is necessary to have multiple active autoselective discharges within the filter at any one time. This was achieved using separately stabilised multiple high voltage electrodes arranged in a regular interlocking (tessellated) electrode arrangement. Examples are shown in Figure 17.

The hexagonal electrode arrangement allows an efficient tessellation pattern and requires relatively few electrodes inserted within the filter volume. Flow mapping data, shown in Figure 18(a) for the hexagonal electrode array show that the regeneration is non-uniform and there are regions that are not regenerated by the plasma. A linear electrode arrangement (shown with a diagonal electrode

orientation) improves the regeneration distribution, shown in Figure 18(b), although the tessellation is more difficult and the interaction between adjacent electrodes becomes more important. The checkerboard electrode arrangement allows good tessellation efficiency and even regeneration but requires a larger number of electrodes inserted in the filter.

Figure 17 Examples of electrode tessellations used shown looking at the front face of a wall flow DPF

Multiple HV electrodes could be connected together, branching from a single power supply to result in one autoselective discharge cleaning a region around multiple inserted electrodes. This allowed the number of active autoselective discharges to be varied independently of the filter size. A selection of the key test results follow.

Figure 18 Flow map results showing regeneration distribution for (a) typical hexagonal electrode arrangement and (b) a typical linear electrode arrangement

ON-RIG DEMONSTRATION

The autoselective regeneration system with inserted electrodes using the checkerboard electrode arrangement was implemented with a 100 cpsi (cells per square inch) 2.4 litre cordierite WFF preloaded to ~4.5 g litre⁻¹. The test exhaust gas conditions were 220 kg h⁻¹ flow rate at 200°C without dilution and without additional PM loading. The power supply consumed ~400 W (from the main power source) when the autoselective discharge was active. The regeneration system was active for 130 minutes.

This regeneration reduced the filter back pressure from ~10 kPa to ~3 kPa, shown in Figure 19. Most of the effect was during the first 40 minutes. This was anticipated as the early part of this test would have reduced the PM loading to levels at which the regeneration rate is reduced (described earlier in Figure 16). If there was incident PM during the test, as would be in the real engine, then the PM loading would not have dropped as far and the regeneration rate would have been sustained.

Figure 19 Corrected back pressure measurements from a hot flow rig test

Following the test, the filter was flow mapped to investigate the regeneration distribution. A typical sample of this flow map is shown in Figure 20. The regeneration distribution is very good across the entire filter. It can be seen that the channels without electrodes were not cleaned as much as the channels with electrodes inserted. If over time there are regions of the filter within which the PM loading gradually builds up, it will become a preferential location for the autoselective discharge and will be subsequently regenerated.

Figure 20 Flow map of a section of the filter showing regeneration distribution of the checkerboard electrode arrangement

ON-ENGINE DEMONSTRATION

A 100 cpsi 2.4 litre cordierite wall flow DPF was installed on the previously described engine test rig. A checkerboard electrode arrangement was used and the autoselective discharge power supply switched on once the PM loading within the filter had reached $\sim 4 \text{ g litre}^{-1}$ with a steady PM loading rate of $\sim 2.1 \text{ g h}^{-1} \text{ litre}^{-1}$. The back pressure was monitored throughout the test and (for the period when the autoselective regeneration was active) is shown in Figure 21. Throughout the test the change of filter back pressure is minimal. This shows that the regeneration rate was approximately equal to the

rate of PM production from the engine. As will be discussed in the following section, the regeneration rate of the autoselective system can be changed by altering the number of autoselective discharges active at any one time as well as some of the electrical factors previously described.

Figure 21 Back pressure data from engine testing of the autoselective DPF regeneration system

SYSTEM OVERVIEW

The work presented earlier in this paper has shown the fundamental behaviour of the autoselective regeneration process and demonstrated it with rig and engine testing. When considering applying this to a vehicle or installation the scalability of the system becomes important. The following discussion summarises some of the considerations when implementing this system.

Choosing the number of active autoselective discharges

A single autoselective discharge within a wall flow DPF will regenerate at approximately a given rate, typically 0.025 g h^{-1} , for each wall that the plasma passes through. For the smallest electrode separations (i.e. the checkerboard electrode array) the regeneration rate per autoselective discharge was $\sim 0.05 \text{ g h}^{-1}$.

Taking an example target of 5 g h^{-1} regeneration rate, 100 active autoselective discharges would be needed. For the linear electrode array shown in Figure 17, the regeneration rate per discharge is $\sim 0.1 \text{ g h}^{-1}$, i.e. 50 active autoselective discharges for the same scenario. The number of active plasmas directly affects the number of stabilised outputs from the power supply but not the power supply size. The bulk of the power supply volume is high voltage insulation. As the electrode separation reduces (i.e. towards the checkerboard electrode array) the peak electrode voltage reduces and the amount of insulation required on the power supply reduces. The power supply for the checkerboard array example would be, therefore, significantly smaller than twice the size of the linear electrode array example.

Choosing the Filter Size

The autoselective regeneration system, in principle, can be applied independently of filter size, provided there is at least 1 high voltage electrode for each required autoselective discharge. The chosen filter size can, therefore be matched to the application.

In most cases, multiple inserted electrodes will need to be connected to a single stabilised power supply output. This will generate one autoselective discharge from the branching high voltage electrodes. Two simplified examples are shown schematically in Figure 22. The number of electrodes connected to a single branch can be chosen to suit the filter size while still achieving the required regeneration rate.

Figure 22 Schematic showing the branching of electrodes and effect on regeneration characteristics

Power Consumption

The power consumed by the autoselective discharge is a function of the plasma length. The regeneration rate also scales with plasma length resulting in the electrical power requirement being described well by the regeneration effectiveness. For the inserted electrode arrangements described, this is $\sim 20 \text{ g h}^{-1} \text{ kW}^{-1}$.

For example, if enough active autoselective discharges are used to achieve a target regeneration rate of 5 g h^{-1} then the power required at the electrodes can be calculated as 250 W. Depending on the power supply design and its efficiency, a typical power consumption for the scenario presented would be 300-400 W.

CONCLUSIONS

A novel plasma based oxidative diesel particulate filter regeneration system (i.e. the autoselective regeneration system) has for the first time been presented. This autoselective regeneration process is aimed at, but not limited to, continuous controlled regeneration of DPFs. Key results from experimental investigations were shown and the regeneration process demonstrated on engine.

Key conclusions from this research are:

1. The autoselective regeneration system has been shown to be capable of regenerating PM trapped on

a wall flow DPF using low power without a catalyst at all expected diesel engine exhaust conditions.

2. The autoselective regeneration system can be scaled and adapted to suit specific applications and allows engineers to determine optimum DPF sizes relatively independently of the regeneration system.
3. The autoselective plasma power supply uses only standard electronic and electrical components that are already produced in high volumes. It is, therefore, expected to be a low cost system.
4. The regeneration rate is a function of the length of the autoselective discharge and the number of active autoselective discharges within the filter. Typical values are $\sim 0.05 \text{ g h}^{-1}$ for each filter wall an autoselective discharge passes through.
5. Regeneration effectiveness (i.e. regeneration rate per unit power) is typically $20 \text{ g h}^{-1} \text{ kW}^{-1}$ and is relatively independent of electrode arrangement. The electrical power consumption by the plasma for any scenario can be estimated from this and the target regeneration rate.
6. An example system with the checkerboard electrode arrangement was demonstrated on engine to regenerate the equivalent of 5 g h^{-1} engine-out PM using $\sim 400 \text{ W}$.

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REFERENCES

1. Society of Motor Manufacturers and Traders Ltd (on behalf of DTI), "Foresight Vehicle Technology Roadmap: Technology and Research Directions for Future Road Vehicles", Version 2.0 (2004)
2. J.S. Howitt and M.R. Montierth, "Cellular Ceramic Diesel Particulate Filter" SAE Technical Paper Series 810114 (1981)
3. Z.G. Lui, E.M. Thurow, R. Caldow and T.R. Johnson, "Transient Performance of Diesel Particulate Filters as Measured by an Engine Exhaust Particle Size Spectrometer" SAE Technical Paper Series 2005-01-0185 (2005)
4. A.M. Williams, C.P. Garner and J.G.P. Binner, "Analysis and Optimization of Gelcast Ceramic Foam Diesel Particulate Filter Performance", Proceedings of the IMechE, Part D: Journal of Automobile Engineering, Vol 222, pp 2235-2247 (2008)
5. T. Jacobs, S. Chatterjee, R. Conway, A. Walker, J. Kramer and K. Mueller-Haas, "Development of Partial Filter Technology for HDD Retrofit" SAE Technical Paper Series 2006-01-0213 (2006)
6. P. Zelenka, S. Schmidt, G. Elfinger, "An Active Regeneration Aid as a Key Element for Safe Particulate Trap Use", SAE Technical Paper Series 2001-01-3199 (2001)
7. T. Tao, W.A. Cutler, K. Voss, Q. Wei, "New Catalyzed Cordierite Diesel Particulate Filters for

Heavy Duty Applications", SAE Technical Paper Series 2003-01-3166 (2003)

8. M. Okubo, T. Kuroki, Y. Miyairi, T. Yamamoto, "Low-temperature Soot Incineration of Diesel Particulate Filter Using Remote Nonthermal Plasma Induced by a Pulsed Dielectric Barrier Discharge", IEEE Transactions on Industry Applications, Vol 40, No 6, pp 1504-1512 (2004)
9. Y. Ichikawa, S Yamada and T. Yamada, "Development of Wall-Flow Type Diesel Particulate Filter System with Efficient Reverse Pulse Air Regeneration", SAE Technical Paper Series 950735 (1995)
10. C.P. Garner and J.C. Dent, "Development of a Microwave Diesel Particulate Trap Regeneration System", Presented at 23rd FISITA Congress, Torino, Italy 7-11 May, Paper 905116 (1990)
11. M. Aria, S. Miyashita and K. Sato, "Development and Selection of Diesel Particulate Trap Regeneration System", SAE Technical Paper Series 870012 (1987)
12. M. Gautam, S. Popuri, B. Rankin and M. Seehra, "Development of a Microwave Assisted Regeneration System for a Ceramic Diesel Particulate System", SAE Technical Paper Series 1999-01-3565 (1999)
13. P. Richards and W. Kalischewski, "Results from a ¼ million km, heavy duty truck trial, using FBC regenerated DPFs", SAE Technical Paper Series 2004-01-0074 (2004)
14. P. Singh, A.M. Thalagavara, J.D. Naber, J.H. Johnson and S.T. Bagley, "An Experimental Study of Active Regeneration of an Advanced Catalyzed Particulate Filter by Diesel Fuel Injection Upstream of an Oxidation Catalyst", SAE Technical Paper Series 2006-01-0879 (2006)
15. M. Okubo, T. Miyashita, T. Kuroki, S. Miwa and T. Yamamoto, "Regeneration of Diesel Particulate Filter Using Nonthermal Plasma Without Catalyst", IEEE Transactions on Industry Applications, Vol 40, No 6, pp1451-1458 (2004)
16. S. Chatterjee, R. Conway and A.P. Walker, "Emission Reduction in On-Road Heavy Duty Diesel Applications with the Continuously Regenerating Technology (CRT) Diesel Particulate Filter", SAE Technical Paper Series 2001-28-0049 (2001)
17. A.M. Williams and C.P. Garner, "Correcting Mass Measurement of Diesel Particulate Filters and Non-Ambient Temperatures", Proceedings of the IMechE, Part D: Journal of Automobile Engineering, Vol 223, pp 99-105 (2009)
18. A. Schmidt-Ott, "New Approached to In Situ Characterization of Ultrafine Agglomerates", Journal of Aerosol Science, Vol 19, No 5, pp 553-563 (1988)
19. A.K.K. Virtanen, J.M. Ristimäki, K.M. Vaaraslahti and J. Keskinen, "Effect of Engine Load on Diesel Soot Particles", Environmental Science and Technology, Vol 38, pp 2551-2556 (2004)
20. M. Sharma, A.K. Agarwal and K.V.L. Bharathi, "Characterisation of Exhaust Particulates from Diesel

Engine", Atmospheric Environment, Vol 39, pp 3023-3028 (2005)

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

Definitions:

d_b	PM mobility diameter
d_r	PM fractal dimension
Δm	change in mass
P	electrical power consumption
P_{BMEP}	brake mean effective pressure
r	regeneration effectiveness
R	regeneration rate
t	time
ρ_{PM}	PM bulk density

Acronyms:

cpsi	cells per square inch
DBD	dielectric barrier discharge
DoE	design of experiments
DPF	diesel particulate filter
HV	high voltage
IC	internal combustion
NO _x	nitrogen oxides
PM	particulate matter
RMS	root mean square
WFF	wall flow filter