

Non-thermal plasma based technologies for the after-treatment of automotive exhaust particulates and marine diesel exhaust NOx

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ABSTRACT

The trend in environmental legislation is such that primary engine modifications will not be sufficient to meet all future emissions requirements and exhaust aftertreatment technologies will need to be employed. One potential solution that is well placed to meet those requirements is non-thermal plasma technology. This paper will describe our work with some of our partners in the development of a plasma based diesel particulate filter (DPF) and plasma assisted catalytic reduction (PACR) for NOx removal.

This paper describes the development of non-thermal plasma technology for the aftertreatment of particulates from a passenger car engine and NOx from a marine diesel exhaust application.

INTRODUCTION

Accentus plc. and J. Eberspächer GmbH&Co. KG have been working to develop non-thermal plasma regenerated DPF technology for diesel passenger car applications. The results from the evaluation of a prototype system on a 3.0 litre, DI turbo-charged diesel engine will be presented. During the evaluation filtration efficiencies between 95 and 100% were recorded with regeneration demonstrated at plasma powers down to 500W at a range of exhaust gas temperatures. The evaluation also demonstrates the possibility for a flexible control strategy, which could be based around either continuous or intermittent regeneration.

The United Kingdom Ministry of Defence (Navy) is evaluating the feasibility of exhaust control technologies suitable for the reduction of NOx emissions from diesel engines. The plasma assisted catalysis approach can offer a number of potential advantages over the use of Selective

Catalytic Reduction in a warship application such as low load performance and the removal of the need for a urea based reductant. A development programme is underway to produce a PACR system for NOx removal. This programme has been based on understanding the process at the laboratory scale and then undertaking the design, build and testing of a system to treat 1/10th the flow from a 1.4MW marine diesel engine. The overall strategy for the programme will be described together with results from the programme to date including the initial testing of the 1/10th scale system.

DIESEL PARTICULATE FILTER (DPF)

Dielectric barrier discharge

The diesel particulate filter, Electrocat™, comprises of a dielectric barrier discharge. The particulates are trapped on a suitable medium and oxidised by the radicals produced by the plasma discharge[1].

Figure 1 shows the schematic of the diesel particulate filter (DPF). Exhaust gas enters the system and flows in the space between the dielectric barrier and the earth electrode. The earth electrode is composed of a sintered metal mesh to allow the exhaust gas to exit the system. Previously ceramic beads were used as the filter medium, which allowed the plasma to be generated in the spaces between the beads. Use of this trapping medium however gave rise to filtration efficiencies of 50 -60% limiting the ultimate performance of the system.

Filtration efficiency improvement

The main thrust of the DPF development has been to improve the filtration efficiency by evaluating a number of alternative media including, cordierite monoliths, ceramic

fibres, foams, and sintered metal meshes. Each material has had their trapping efficiency and their ability to support the generation of the plasma evaluated. These tests were carried out using a small laboratory scale plasma discharge system. In the case of the metallic mesh, this forms the earth electrode

since it is a conductor. These new media have all produced higher filtration efficiencies than the ceramic beads, with typical values of 80-90% or higher, as shown in Figure 2.

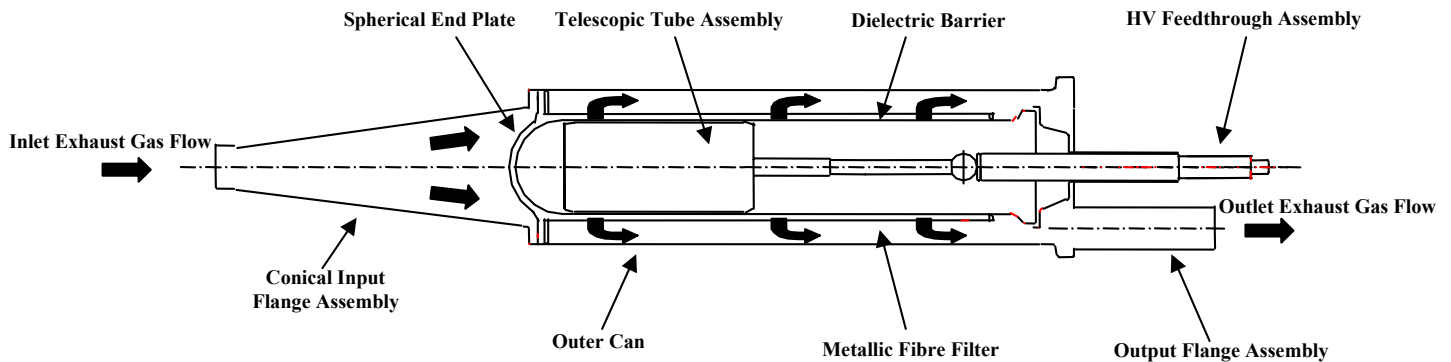


Figure 1 The Electrocat™ Diesel Particulate Filter (DPF)

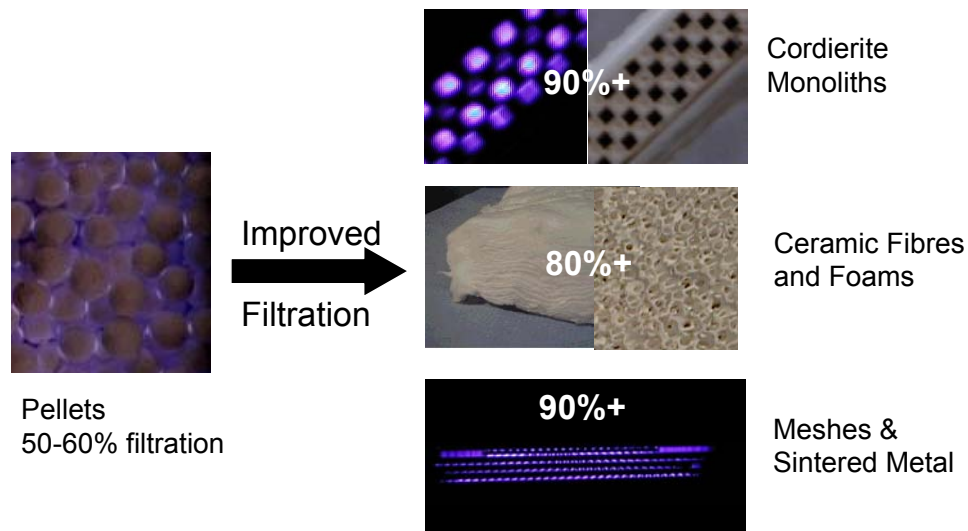


Figure 2 Filtration efficiencies of the trapping media

The sintered metal mesh filtration medium demonstrated the required performance levels and was the most practical filter medium and so was subsequently incorporated into a full scale Electrocat™ DPF. Figure 3 shows a photograph of the full scale system with the outer can removed. The Electrocat™ DPF was then tested using a 3 litre diesel engine from a passenger car on the engine test cell facilities at Eberspächer.

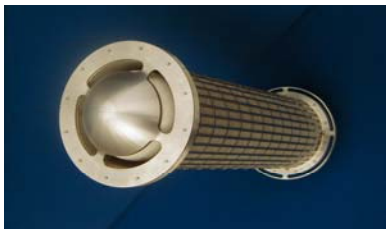


Figure 3 The Electrocat™ DPF

Engine testing of the Electrocat™ DPF

A schematic of the set up (Figure 4) shows the DPF situated downstream of a diesel oxidation catalyst (DOC). Measurements were made of the temperature at various points around the system. The pressure was measured at the inlet and outlet of the DPF together with the smoke level in the exhaust at the inlet and outlet of the DPF.

Figure 5 illustrates the DPF filtration efficiency measured at a constant engine speed of 1500rpm for a variety of engine torque values. The soot loading on the filter was increased by increasing the torque from the engine from 60 to 260 Nm in 30Nm steps. The plot shows the particulate matter concentration before and after the DPF. Initially the physical filtration efficiency for this clean system starts at a value of approximately 80%. As soot is deposited in the filter medium this efficiency rises until it reaches a value approaching

>>99%, achieving the targeted high filtration efficiency required.

The ability of the plasma DPF to regenerate a soot loaded filter is shown in Figure 6. This shows the backpressure due to the DPF and torque as a function of time for a constant engine speed of 2000 rpm. Initially at a torque of 150 Nm the DPF was loaded with soot, with no plasma applied, resulting in a rising backpressure trend as expected. The engine torque was then increased to 237 Nm and the back pressure allowed to stabilise. At this point the back pressure slowly decreased due

to thermal regeneration at an exhaust temperature of 375-400°C. When plasma power was then applied the backpressure reduced significantly over a short period of time indicating the plasma regeneration of the DPF (Figure 6).

Figure 7 illustrates this behavior over a number of repetitive cycles demonstrating the high reproducibility of the regeneration process.

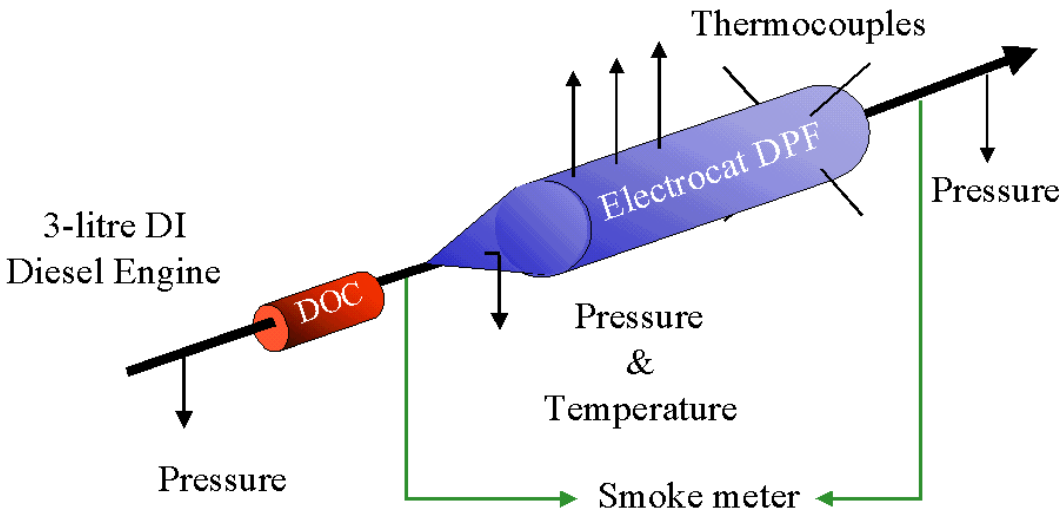


Figure 4 The test cell arrangement for testing the Electrocat™ DPF

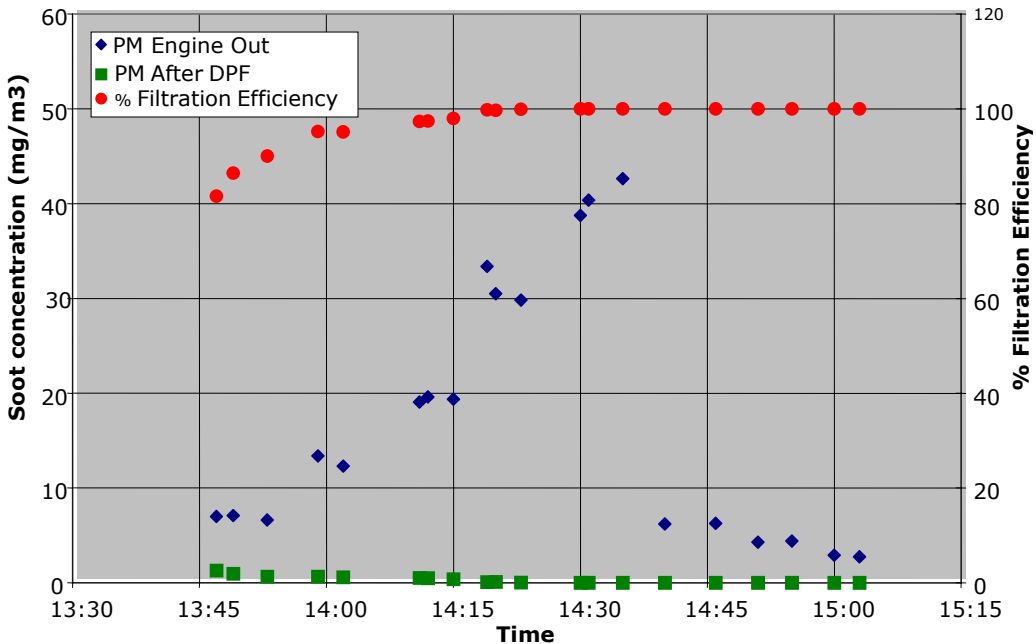


Figure 5 Filtration efficiency of the Electrocat™ DPF

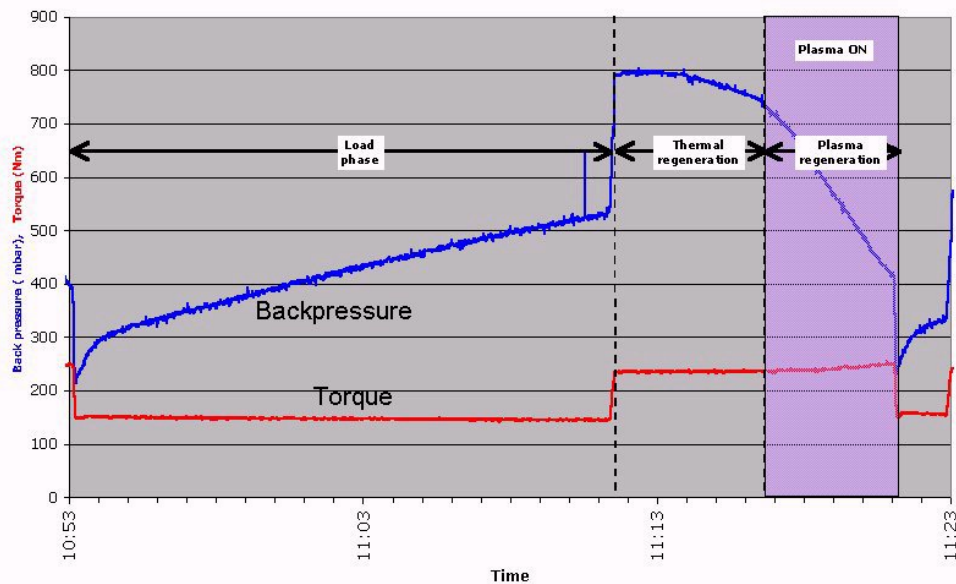


Figure 6 Loading and regeneration of the Electrocat™ DPF

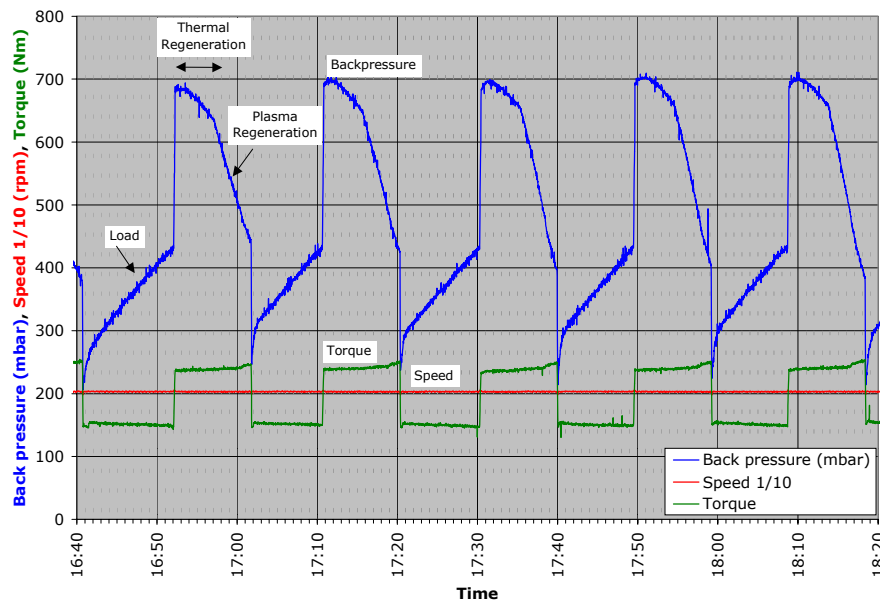


Figure 7 Cyclic loading and regeneration of the Electrocat™ DPF

Non thermal plasma DPF summary and conclusions

The performance of the Electrocat™ non-thermal plasma DPF has shown significant progress. The improved filtration media show efficiencies in the range 95 to >99%. Testing of the system has shown rapid initiation of the regeneration of the DPF on application of the plasma power and this has been demonstrated at plasma powers down to 500W. Over an intermittent regeneration cycle the average power would be less than the applied plasma power. This regeneration can be achieved over a variety of exhaust temperatures including the 90-200°C range typical of urban driving.

In terms of the future development of the system the emphasis will be on increasing the capacity of the system i.e.

increasing surface area of the filter to lower overall DPF back pressure and improving the performance and power efficiency. This will allow the system to operate over the full range of operating conditions allowing a flexible operating strategy to be developed and meet the requirements for application in passenger vehicles.

PLASMA ASSISTED CATALYSIS OF NO_x FOR MARINE DIESEL EXHAUST

Drivers for emissions reduction from marine diesels and Royal Navy requirements

World shipping produces approximately 7% of the world's NO_x inventory. Marine legislation tends to lag behind that for automotive and other industries. MARPOL Annex VI

[2] was adopted in 1997 and places limits on the NO_x emissions from ships. It will come into force one year after being ratified by 15 states with at least 50% of the world's shipping tonnage. At the time of writing it has been ratified by 11 states with 53.84% of the world's tonnage. Figure 8 shows the NO_x emissions limits from MARPOL Annex VI. These limits can generally be met by modern diesel engines without recourse to aftertreatment. Further reductions in NO_x emissions can be envisaged from primary engine methods such as EGR, emulsified fuels, water injection etc.

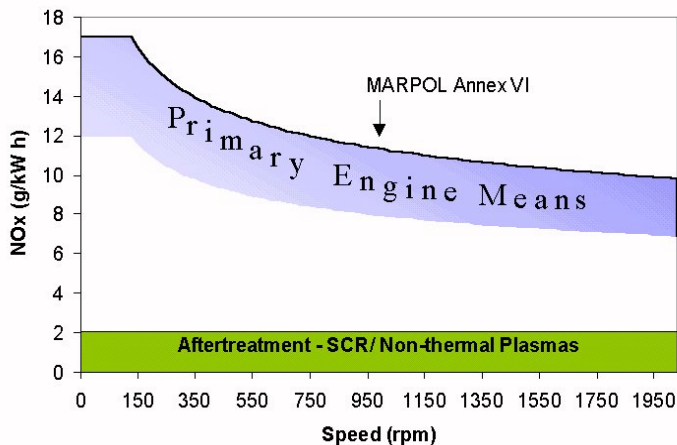


Figure 8 MARPOL Annex VI NO_x emissions limits

A number of vessels are using Selective Catalytic Reduction (SCR) to reduce NO_x emissions particularly in shipping areas which apply port differential fees and fairway dues (e.g. Baltic area) according to the level of NO_x emissions and make it commercially sensible to use an aftertreatment system. The existence of such a technology may itself drive the levels of NO_x emissions for future legislation. Furthermore, future legislation may place limits on emissions of additional pollutants such as particulates for which no legislation exists at present.

The Royal Navy is required to comply with all international conventions to which the UK is a signatory and must also comply with all local regulations. An SCR system has been tested on a 1.4MW Paxman Valenta engine. Although this system produced high levels of NO_x reduction there are concerns over the low load and shock performance of an SCR system. In addition there are concerns over the use of a urea reductant. For the Royal Navy to have a worldwide operational capability the urea reductant would need to be available throughout the world. This reductant would also require storage on the warships where space is limited particularly if it was required to be stored as a solid and then made up into the appropriate aqueous solution.

It is not economically effective to fit any aftertreatment system simply to comply with current local regulations. Any aftertreatment system would be required for future more stringent legislation. Given the concerns over the use of an

SCR system the question arises as to whether plasma assisted catalysis of NO_x could allow the Royal Navy to meet potential future legislation.

Plasma assisted catalysis of NO_x and its application to marine diesel exhaust emissions

Figure 9 shows the general principle of the PACR of NO_x [3]. The plasma creates radicals which react with the hydrocarbons (HC) in the exhaust to produce activated hydrocarbons (HC*) which promote the catalysis of NO_x. There are not enough hydrocarbons in the exhaust and this reductant must be added to the exhaust. However this reductant can be the diesel fuel itself thus eliminating the need for storage of an additional material such as urea. Furthermore, as described in the previous section, the plasma may also be used to remove the particulates. Thus the non-thermal plasma system is well placed to meet future legislation.

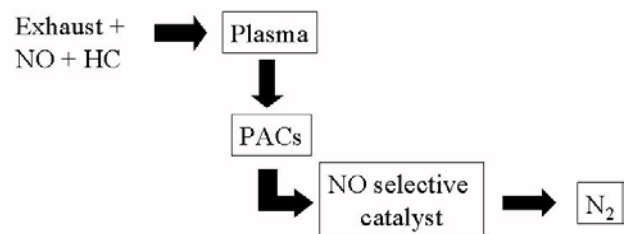


Figure 9 The plasma assisted catalysis of NO_x

In particular, the requirements for a non-thermal plasma system for marine diesel exhaust are:

- NO_x reduction comparable to that of an SCR system
- As in the case of the SCR system the non-thermal plasma would replace the silencer and thus the noise attenuation must be > 25 dB, the weight of the system should be no more than 20-50% greater than the silencer and the space requirements should be no more than that for the silencer.
- The overall power usage should be no more than 5% of the engine power. There will be a penalty in using the diesel fuel as a reductant and this is estimated to be of the order of 2-5%.
- The system should be overhauled only as frequently as the engine.

The non-thermal plasma development programme

The development of the non-thermal plasma assisted catalysis of NO_x for marine diesel exhausts has been based on a staged approach as shown in Figure 10.

An initial laboratory stage demonstrated the basic principle of the process. This is followed by the design, build and testing of a 1/10th scale system and finally by the building of a full scale system. This programme would make use of developments from the Electrocat™ programme such as the dielectric barrier discharge and power supply technology. The programme is currently at the stage of testing and evaluating the 1/10th scale system. The term 1/10th scale refers to treating

the 1/10th the exhaust flow of an indicative engine such as a 12RPA200 Paxman Valenta which generates 1.4MW. At rated speed and power the exhaust flow is approximately 8200 kg/hr.

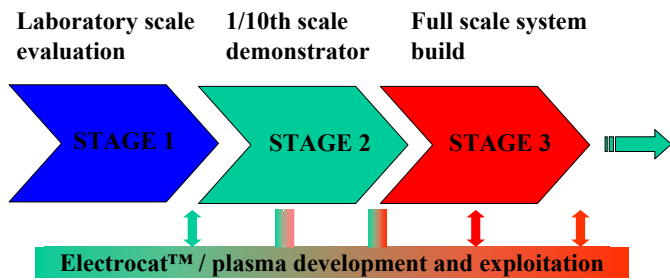


Figure 10 The non-thermal plasma development programme

NOx reduction in synthetic and genset exhaust at laboratory scale

The selection of the NOx catalyst was carried out using a small laboratory scale plasma and catalyst system. The NOx reduction was demonstrated both with synthetic exhaust and with the exhaust from a small genset operating at 2-3kW before proceeding to design and build the 1/10th scale system.

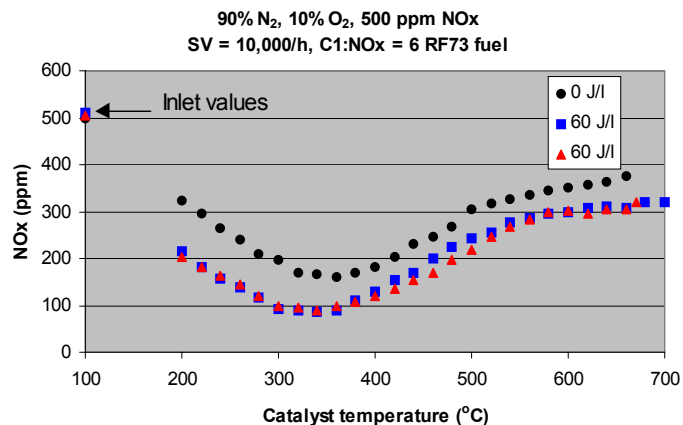
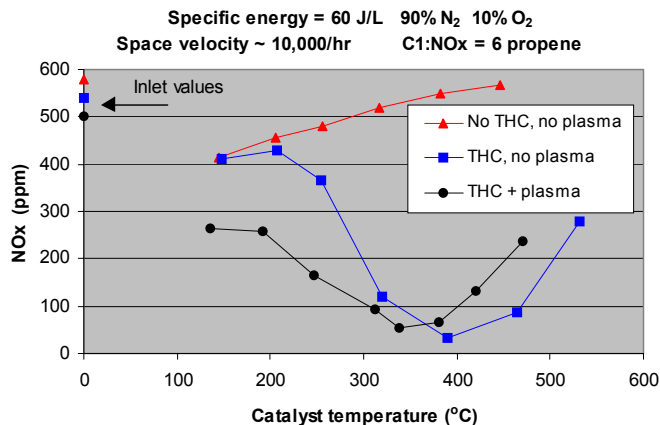


Figure 11 Plasma assisted catalytic reduction of NOx in synthetic exhaust for propene and diesel fuel reductant

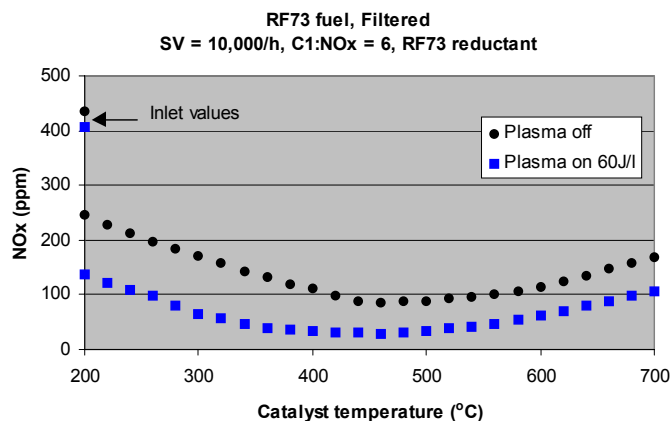
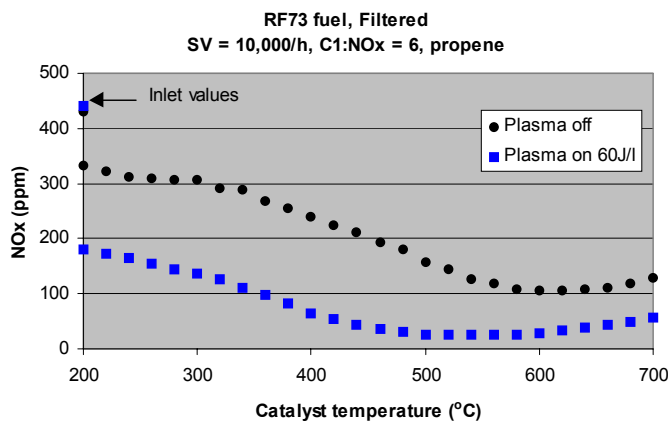


Figure 12 Plasma assisted catalytic reduction of NOx in genset exhaust for propene and diesel fuel reductant

The 1/10th scale system design

The approach taken for the design of the 1/10th scale system was not one of scaling up the laboratory scale system. The 1/10th scale design is based on an (evolving) concept for a full scale system. This full scale system would match the envelope available for an example fit - in case for a Type 23 Frigate. This approach has a number of advantages. The potential for encountering new development issues will be minimised. The approach also allows for ship integration and safety issues to be addressed at an early stage. Figure 13 shows the full scale concept design. A divertor valve is used which when closed allows the exhaust gas to flow radially through the plasma and then through the catalyst regions. When the valve is open the exhaust does not flow through the plasma or catalyst and this is to act as a safety feature. The plasma system consists of a number of modules and thus for fits to other classes of vessels the appropriate number of modules can be assembled in the space available. The high voltage power supplies for the plasma modules are close coupled beneath the system.

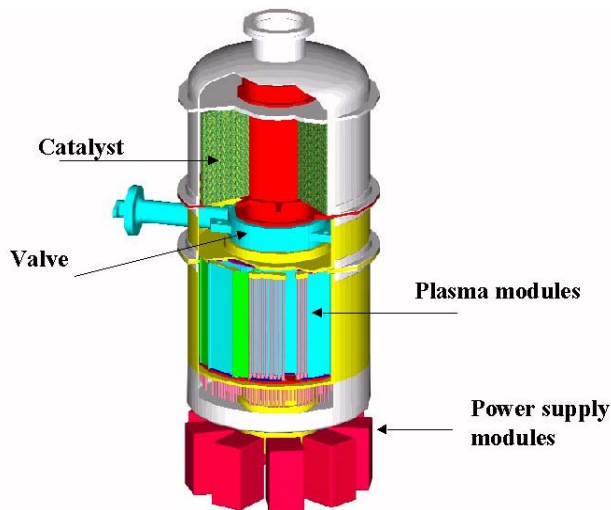


Figure 13 The full scale non-thermal plasma design concept

In Figure 14 the full scale concept is shown within the exhaust system for a Paxman Valenta engine in the Upper Auxiliary Machine Room of a Type 23 Frigate. The non-thermal plasma system has replaced the existing silencer. The power is provided from a 3-phase distribution board lower down in the vessel. This removes the need to run high voltage cables through the vessel as this is a safety issue and also reduces cable losses.

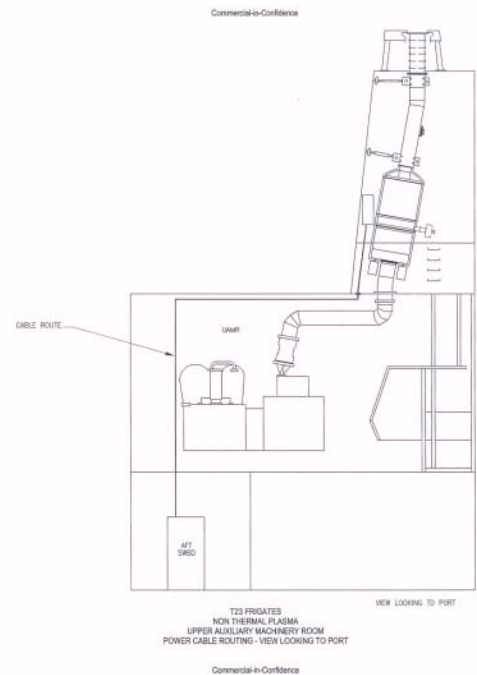


Figure 14 The non-thermal plasma system concept in a Type 23 Frigate

The 1/10th scale system is design to treat a flow of approximately 640 m³/hr. Based on using 5% of the engine power then this corresponds to 7 kW of plasma power for a 1.4 MW engine. The 1/10th scale design is shown in Figure 15. This consists of three plasma/catalyst modules. Exhaust gas enters from the bottom and when the valve is closed the gas flows radially through the plasma and then through the catalyst in each module and then exits through the top.

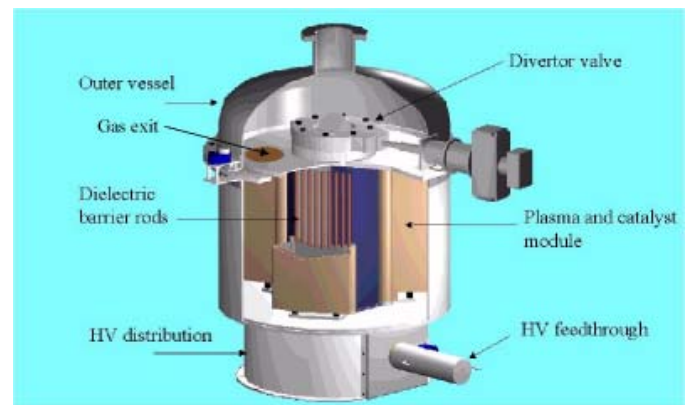


Figure 15 The 1/10th scale system design

The plasma is formed by a number of dielectric barrier rods which have the high voltage electrode coated on the inside. The space between the barriers and the earth electrode is packed with ceramic beads as described earlier. In Figure 16 a photograph of the 1/10th scale system is shown comprising

the plasma/catalyst vessel, the power supply unit and the control, diagnostic and safety system.

In terms of physical size the 1/10th scale system is approximately 0.75 times the diameter and 0.4 times the length of the full scale system.



Figure 16 The 1/10th scale system

The high voltage power supply was rated at 10 kW. The output voltage and frequency can be varied to provide the correct power. The inductance of the high voltage transformer can also be changed by driving the core pieces apart or together using stepper motors. This allows the load to be matched to the power supply to maximise efficiency as the electrical load may have depended on engine operating condition.

Before installation in the engine test cell the system underwent a number of checks using a flow of air instead of exhaust gas. The power capability, power measurements and diagnostics were tested. The electromagnetic compatibility of the system for both radiated and conducted emissions was also tested to ensure the system met European industrial equipment standards.

Testing of the 1/10th scale system in marine diesel exhaust

The 1/10th scale system underwent initial testing at MAN B&W's Paxman Facility in Colchester, Essex, United Kingdom. Testing was carried out using an eighteen cylinder VP185 engine. At rated speed and power the engine develops 3.2MW. The engine fuel was 0.11%wt sulphur A2 distillate. The engine has three exhausts each taken from a group of six cylinders which then merge into a single exhaust line. A slipstream of the exhaust from one bank of six cylinders was used for testing the non-thermal plasma system. The flow through the system any engine mode was controlled using different aperture diameter orifice plates in the pipework to the non-thermal plasma system. Figure 17 shows photographs of

the arrangements with the non-thermal plasma system situated above the dynamometer.



(a) The 18VP185 engine



(b) The non-thermal plasma system



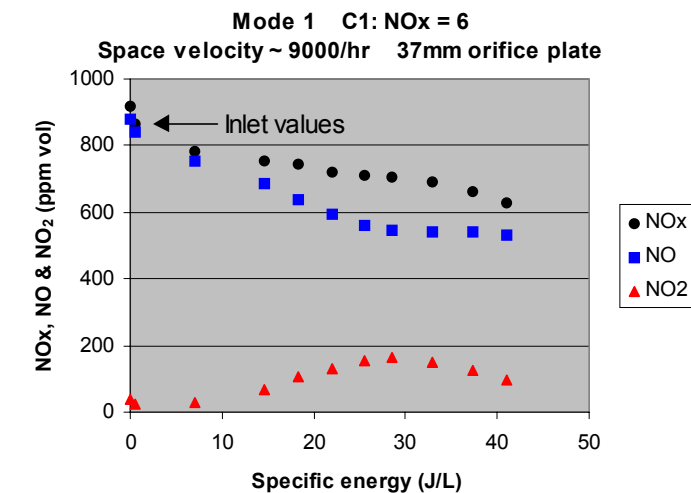
(c) The pipework from the exhaust to the non-thermal plasma system

Figure 17 The engine test cell and the non-thermal plasma system

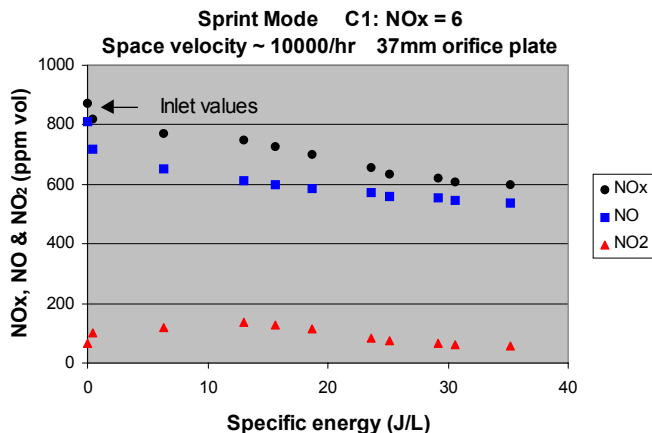
The exhaust was not filtered to remove any particulate matter entering the non-thermal plasma system. Measurements of the exhaust NO_x, total hydrocarbons (THCs), oxygen, carbon monoxide, carbon dioxide, and smoke were made

before and after the non-thermal plasma system together with the exhaust temperature, flow and pressure at various positions around the system. Propene was used as the reductant.

In Figure 18 the measurements of the NO_x abatement by the non-thermal plasma system is shown as a function of the specific energy input to the exhaust with the engine operating in two engine modes i.e. Mode 1 of the ISO8178 D2 Cycle corresponding to rated speed and power (1800 rpm, 3.2MW) and the "Sprint" mode (1950rpm, 4MW). The NO_x level does reduce with increasing specific energy but the highest NO_x reduction measured was 30-40% which is somewhat less than that measured in the laboratory scale trials. The NO_x reduction is limited by the ability to remove of the NO component. In the case of the "Sprint" mode the catalyst temperature was measured as being 400°C and thus should have been high enough to produce greater levels of NO_x reduction.



(a) Rated speed and power (1800 rpm, 3.25 MW)



(b) "Sprint mode" (1950 rpm, 4 MW)

Figure 18 NO_x reduction as a function of specific energy at two engine operating conditions

1/10th scale versus laboratory scale performance

The present emphasis of the work is to understand and remedy the difference in the NO_x reduction levels measured using the laboratory scale system and the 1/10th scale system.

During the initial engine test cell trials a number of issues, which may have caused a difference in performance were checked.

1. An error in the power measurements would lead to an error in the specific energy. The power measurement was checked and found to be working correctly.
2. If the flow measurement was incorrect then the specific energy and the space velocity would be in error. The flow measurement was checked using an independent flow measurement meter and found to be correct.
3. The gas flow through the plasma/catalyst modules may not be uniform due to pressure non-uniformity across the face of the module when the gas is diverted radially. In order to investigate this possibility the catalyst was removed from the modules and new cylindrical catalyst units were installed underneath the gas exit ports in the valve plate. These are believed to give a known uniform gas distribution through the catalyst but no improvement in performance was measured.

A number of other possibilities may have caused the difference in performance. An analysis of the used catalyst was carried out and this indicated the presence of both sulphur (from the fuel) and carbon (from particulate matter) on the catalyst. These elements may have a detrimental effect on the performance of the system.

The effect of fuel sulphur content

The fuel used in the testing at the laboratory scale had a fuel sulphur level of 0.043%_{m/m} whereas that used in the testing of the 1/10th scale system had a sulphur content of 0.11%_{m/m} and sulphur is a known catalyst poison. The Royal Navy uses fuel which complies with the NATO F76 specification. This allows the sulphur content of the fuel to have a maximum value of 1%. Thus it is important to understand the effect of the fuel sulphur level.

Initial tests of the effect of the fuel sulphur level are being carried out at the laboratory scale. Figure 19 illustrates the PACR of NO_x at a fixed catalyst temperature of 420 °C in genset exhaust. The fuel used by the genset was F76 with a sulphur content of 0.12% (matching that used in the test cell trials). The NO_x reduction remains high over a period of approximately three hours without degradation.

Any catalyst material for use in a marine diesel exhaust must be able to tolerate the presence of the sulphur dioxide from the fuel combustion, up to the maximum fuel sulphur level, for very much longer periods.

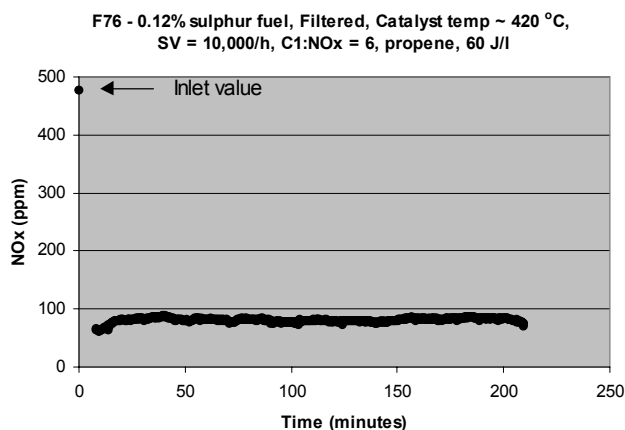


Figure 19 Plasma assisted catalytic NOx reduction at a fixed catalyst temperature in genset exhaust using 0.12% m/m sulphur fuel

The effect of particulates in the exhaust

If the particulates in the exhaust are not efficiently trapped and oxidised then there can be a detrimental effect on the reduction of NOx.

The plasma modules in the 1/10th scale system were packed with ceramic pellets. If the particulates trapped in the plasma module are not efficiently oxidised then this can lead to reduced plasma generation due to a build up of a conducting layer although power is still be consumed by the system. The effect of this will be to reduce the level of activation of the reductant and hence the level of NOx reduction.

It was shown earlier that the ceramic pellets do not have a very high filtration efficiency (~50-60%). Thus some of the particulate matter could be deposited on the catalyst material. Carbonaceous material was found on the catalyst. This would lead to blocking of the active sites and thus a lower level of NOx reduction.

In order to investigate this possibility the system could be tested with a particulate trap before the system in order to remove any particulates before the catalyst.

Plasma assisted catalytic reduction of NOx for marine diesel engines summary and conclusions

Plasma assisted catalytic reduction of NOx has been demonstrated at the laboratory scale and high levels of NOx

reduction have been measured using both propene and diesel fuel as the reductant. Based on a full scale concept design, a 1/10th scale non-thermal plasma system has been designed and built for the treatment of marine diesel exhaust emissions. Such a system has a number of advantages over the use of Selective Catalytic Reduction such as the use of the diesel fuel reductant.

Initial trials of the 1/10th scale system demonstrated NOx reduction levels of 30- 40% which was lower than the 80-90% measured in the laboratory scale systems. This difference in performance is currently being investigated. The effect of fuel sulphur on catalyst performance is being studied for a number of different catalyst formulations. This will be an important issue for any marine diesel exhaust aftertreatment system due to the relatively high levels of sulphur in marine diesel fuel. The possibility that particulate matter caused deterioration in performance is also being investigated.

The aim is to carry out further trials of the 1/10th scale system in order to demonstrate the viability of the use of plasma assisted catalytic reduction of NOx for marine diesel exhaust emissions.

ACKNOWLEDGMENTS

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