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Investigation and Development of the Diesel Particulate Filter Autoselective Regeneration System

by

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M.Eng (Hons)

A Doctoral Thesis submitted in partial fulfilment of the requirements for the award of Doctor of Philosophy of Loughborough University

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Abstract

This thesis discusses an investigation and initial development of a novel Autoselective discharge system for the regeneration of diesel particulate filters.

Numerous previous studies have indicated that diesel exhaust particulate aerosols can have significant health impacts on humans. These findings have lead to legislation that limits the emission of combustion generated particulate matter (PM) and has spurred the widespread development of diesel particulate filters. These filters can reduce exhaust PM emissions by over 90% but they require regular cleaning or 'regeneration' to prevent the exhaust gas flow pressure drop increasing to the extent where it has detrimental affects on-engine performance. The novel Autoselective system investigated in this research uses an atmospheric pressure electric discharge to regenerate diesel filters by the efficient oxidation of the trapped PM within the filter.

In this research the fundamental characteristics of the atmospheric pressure discharge were investigated to allow maximisation of regeneration rate whilst minimising energy consumption. The Autoselective discharge was tested in a controllable rig that simulated a diesel engine exhaust gas flow environment. The affects of varying gas flow dynamics and compositions were investigated, and a system was developed that enabled the discharge to regenerate the full filter volume. The performance characteristics of a prototype system were investigated using Design of Experiments (DoE) techniques and response surface models developed to calculate the PM oxidation rate under various environmental operating conditions. The operation of the system was further investigated using other experimental procedures and apparatus developed during the research (e.g. quasi continuous mass measurement apparatus), which provided further insights into the characteristics of the system.

The research demonstrated that the Autoselective discharge could be used in an energy efficient system to controllably regenerate standard Cordierite wall flow
diesel particulate filters in the exhaust system of diesel engines under all likely exhaust flow conditions.
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1 Introduction to the Autoselective System

The diesel engine proved an efficient and reliable source of useful power for much of the 20th century. The dominance of commercial applications and the recent expansion into the passenger car market mean that the diesel engine is likely to continue to be a very important power source in the 21st century.

Diesel engines offer significant thermodynamic efficiency benefits compared to the gasoline engines because of the higher compression ratio and load control using fuel metering only rather than also using air throttling. The superior low speed torque characteristics of the diesel engine make it more usable for many applications, and the relative safety of diesel fuel also provides a significant advantage. The on-set of detonation or knock imposes limits on the physical cylinder size of gasoline engines, allowing diesel engines to dominate large capacity, high power applications (Taylor, 1985).

Improvements in diesel engine refinement and performance along with vehicle tax laws based on CO₂ emissions have all contributed to increasing diesel sales in the
European and US passenger car markets. In 2002 engineering consultants Ricardo Plc estimated that diesel engines would account for 50% of the passenger car and light commercial vehicle sales in Europe by the end of 2005. By 2007 vehicle manufacturers are expected to offer customers the same number of diesel variants as gasoline for each vehicle.

However, diesel engines emit combustion generated particulate matter (PM), even with the use of modern high pressure fuel injection systems and strategies. These particulates vary in diameter between 0.01 μm and 10 μm, with the smaller range being easily inhaled by humans.

This thesis reports research on a novel diesel engine exhaust aftertreatment method for reducing PM emissions. In the following sections of this first chapter, the fundamentals of PM will be discussed followed by a presentation of diesel emissions legislation and control. It will then provide an overview of the whole thesis and will state the major contributions to knowledge that this research has provided.

1.1 \textit{Particulate Matter (PM)}

Transportation is responsible for a large percentage of total human caused PM pollution. However, all of this PM does not derive from combustion alone, other significant sources are the abrasion of tyres, road surfaces, brakes and clutches (Harrison, 1999).

Combustion generated PM does not refer to the visible black, blue or white clouds of 'smoke' with which older diesel engines are commonly associated. PM refers primarily to the microscopic particles that can still be present when the exhaust gas appears clear to the naked eye.

Combustion generated particulates are complex aggregates of solid and liquid material usually consisting of a carbonaceous core on to which condenses heavy
hydrocarbons derived from the fuel and lubricating oil along with small sulphate particles (Kittelson, 1998), see Figure 1-1.

Figure 1-1 – Schematic of diesel particulate structure and constituents

Exhaust particulates are usually divided into soluble and dry fractions. Typically 15 to 30% of the mass is extractable in solution. Although the majority of particulate emissions are formed through incomplete combustion of fuel hydrocarbons, engine lubrication oil also contributes. Trace elements within lubrication oil such as zinc and phosphorus have been found within particulates (Heywood, 1988 (p. 630)).

The mass distribution of diesel particulates is bi-modal, with a nucleation mode (mean characteristic diameter \( \sim 0.3 \mu m \)) and a larger accumulation mode (\( \sim 3 \mu m \)) (see Figure 1-2). The larger particles settle in atmospheric air by the effects of gravity within a few hours, whereas the smallest particles can remain aerosol for many days and can be transported over large distances, increasing the chance of inhalation.

Figure 1-2 – Volume fraction distribution by diameter (Department for the Environment, 1999)
1.1.1 Particulate Formation

Particulate formation is a complex and dynamic process that is significantly influenced by engine in-cylinder conditions. The primary components of PM are spherules. These are formed primarily from carbon in the fuel by processes such as molecular fragmentation, condensation and then polymerisation into larger molecules. These spherules form in the diesel combustion environment despite there being sufficient air present within the cylinder to fully oxidise all the fuel, at temperatures between 1000 and 2800 K and pressures between 500 and 1000 kPa.

After this spherule formation, the nuclei grow in size, with much of the increase in PM mass coming from the absorption of gas phase molecules. This surface growth increases the total mass of the spherules but not the number. Particle growth also occurs through coalescence of spherules, a process that reduces total number of particles but does not change the total mass.

These stages of particulate generation and growth constitute the formation process. At both stages the products can be oxidised to form gaseous products such as CO and CO₂. The net amount of PM emitted from the engine depends on the balance between formation and oxidation processes. Absorption of hydrocarbons through the particle surfaces and condensation of hydrocarbons to form new particles occurs in the exhaust system as the gases cool and dilute.

1.1.2 Gasoline PM

Gasoline engines also emitted PM even when correctly calibrated. Relatively little research has been conducted into gasoline particulate emissions due to the historically larger contribution, on a mass basis, made by diesels. However, the increasingly stringent diesel particulate emissions legislation has spurred research into gasoline particulates.
Gasoline particulate falls into three categories: lead, sulphates and organic particulates or soot. Soot emissions are a result of incomplete combustion of fuel rich mixtures, especially apparent in some gasoline direct injection engines (Greenwood, 1996). Sulphur within the fuel leads to sulphate formation during combustion and subsequent exhaust catalyst processes generate sulphuric acid aerosol. Lead particulate emissions were historically generated from burning leaded fuel in engines, but these have been reduced significantly by the current use of unleaded fuel.

Combustion generated automotive PM is basically carbon particles onto which are absorbed a complex mixture of chemicals sourced mainly from the fuel and lubrication oil. Many of these chemicals are known to be harmful to humans and research into their health effects is ongoing.

1.2 Health Effects of PM Inhalation

The human respiratory system facilitates the gas exchange process for the cardiovascular system, allowing oxygen into the blood stream and removing carbon dioxide. This process occurs within the lung alveoli, which act as the interface between the air and blood vessels.

The respiratory system has a number of mechanisms to remove a moderate amount of inhaled PM such as that generated by diesel engines (see Figure 1-3).
Large particles (> 6 μm) are collected in the nasal passage by hairs. Particles between ~1 μm and ~6 μm are trapped in a mucus layer between the pharynx and terminal bronchi. Small moving hairs (cilia) carry the particle holding mucus into the stomach. Particles < 1 μm can enter the alveoli. Mobile cells known as macrophages engulf any foreign particles that reach the alveoli. The macrophage then migrates to the airway where it is collected by the mucus and transported out of the body. Macrophages work effectively at removing most particles but can become overloaded or outnumbered.

Particles that are not removed by the macrophages and therefore enter the bloodstream can be removed by the lymphatic system, however, this is a much slower process. PM has been found to accumulate at the lymph nodes and although its effect is unclear, it is believed the matter causes increased antigen production.

The respiratory system can become overloaded by high aerosol particle concentrations. When large numbers of unreactive particles are present within the alveoli, there are insufficient macrophages to remove pathogenic particles. More importantly, the larger surface area of an equivalent mass of smaller particles gives them the capacity to transport more toxic substances as well as the ability to outnumber the macrophages (Muzyka et al, 1998). Thus, from a health viewpoint,
smaller particles are potentially much more dangerous and can penetrate deeper into the cardiovascular system, residing in the body much longer than larger particles. Studies have shown that 90% of particles < 6 μm in diameter are cleared within 24 hours, however, only 30% of particles < 1 μm are cleared (Helmer, 1999). Hypotheses suggest that these smaller particles are able to enter the blood stream and have to be cleared by the slower lymphatic system process.

1.2.1 Short Term Health Effects

Evidence from epidemiological studies demonstrates associations between short-term exposure to PM and adverse effects on human health, even at low levels commonly encountered in developed countries. Most recent studies show that PM$_{2.5}$ is a much better predictor of health effects than PM$_{10}$. Current data and studies undertaken in association with the World Health Organisation (WHO) have been unable to define a PM threshold limit below which no adverse health effects occur. An increase of 10 μg.m$^{-3}$ in PM$_{10}$ in Sao Paulo was related to an increase in daily mortality of 3% among adults older than 65 years of age (Saldiva et al, 1995 reported in Helmer, 1999), although the actual aerosol particulate levels were not stated. Studies conducted to determine the impact of PM on respiratory emergencies and medical visits have also suggested a positive correlation (Arranda et al, 1994). An epidemiological study in Japan showed that the prevalence of asthmatic symptoms and chest conditions was significantly correlated with particulate levels (Nitta et al, 1993).

1.2.2 Long Term Health Effects

There is less information on the long-term effects of PM on health. Some studies have suggested there to be a reduction in life expectancy of up to 3 years. Recent studies have shown a prevalence of bronchitis symptoms in children, and reduced lung function in both children and adults. The WHO has not set a guideline as to the safe long term level of particulate exposure. Epidemiological studies in China show
that under long term exposure there is a correlation between particle concentration and mortality from lung cancer. An investigation based on data for 50 million people from 26 Chinese cities showed that where the average PM$_{10}$ pollution concentration doubled there was a corresponding doubling in lung cancer rates (Fang Qisheng, 1991). Other reported effects were chronic broncho-pneumonia and depressed immune function in children. However, other work conducted in Brisbane, Australia, found associations between PM and daily mortality were significant only for individuals who were older than 65 years of age or those with cardiovascular disease.

The mounting evidence of the acute and chronic health effects of PM on humans has spurred governments around the World to introduce legislation to control the emission of PM from automotive sources, currently mainly focused on diesel engines.

1.3 Diesel Emissions Legislation and Particulate Control

The concentration of road traffic emissions in ambient air was initially systematically recorded in California in the 1940s. In Europe, carbon monoxide emissions from road traffic became a matter of concern in the 1960s because of a direct health risk to humans.

Emission control regulations are intended to limit the extent to which automotive sources impact on air quality. Legislative countermeasures were first implemented in the United States with the introduction of the 1961 Emissions Control Regulations in California. The first passenger car emissions control requirements in the European Community became effective in 1970. Legislation subsequently expanded to include heavy-duty vehicles (> 3.5 tons and engine power of > 85 kW) concentrating on gaseous emissions (NO$_x$, CO and HC) (see Figure 1-4), however, PM emissions became legislated in 1993 under Euro I standards.
Particulate emissions legislation is following other automotive emissions standards and becoming more stringent (see Table 1-1).

<table>
<thead>
<tr>
<th>Year</th>
<th>Euro</th>
<th>PM Emissions (g.kW⁻¹.hr⁻¹)</th>
<th>NOₓ Emissions (g.kW⁻¹.hr⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1992</td>
<td>I</td>
<td>0.36</td>
<td>8</td>
</tr>
<tr>
<td>1998</td>
<td>II</td>
<td>0.15</td>
<td>7</td>
</tr>
<tr>
<td>2000</td>
<td>III</td>
<td>0.1</td>
<td>5</td>
</tr>
<tr>
<td>2005</td>
<td>IV</td>
<td>0.02</td>
<td>3.5</td>
</tr>
<tr>
<td>2008</td>
<td>V</td>
<td>0.02</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 1-1 - EU heavy-duty vehicle PM emissions standards

Increasingly stringent emissions legislations applied to heavy-duty diesel engines have required engine manufacturers to develop specific emissions abatement strategies targeting NOₓ and PM. In-cylinder techniques have had significant affects in reducing production of noxious combustion products and have been successful in lowering emissions to meet Euro I, II and III targets.
1.4 In-Cylinder Techniques for Emission Control

Throughout the 1990s up to the present day numerous researchers have developed technologies to reduce engine-out PM by minimising the fuel rich zones and diffusion combustion phases in which they are primarily sourced. Increased in-cylinder air motion can greatly improve fuel air mixing. Such motion is developed through carefully designed swirled intake ports (Lee and Reitz, 2003) and shaped combustion chambers (Wickman et al, 2003) promoting fuel-air mixing. Alongside these air management techniques, fuel injection techniques and control technologies (Hountalas et al, 2003) have made significant improvements in diesel engine refinement as well as engine-out PM levels. Fuel injection pressures have increased to above 150 MPa whilst fuel spray patterns and distribution can be carefully controlled through injector nozzle design. Electronic control of fuelling allows multiple injections per cycle, providing enhanced conditions for the main injection phase improving combustion from both by-product and noise emission viewpoints.

However, the NOX and PM production trade-off adds significant complexity to the situation. In-cylinder techniques used to reduce either regulated combustion product generally lead to increased levels of the other (Ladommatos et al, 1998).

The proposed stringent emissions legislations set requirements that cannot currently be met by in-cylinder controls alone. Thus a range of aftertreatment technologies have been developed including Selective Catalytic Reduction (SCR) (Walker et al, 2003, Schar et al, 2003) and Exhaust Gas Recirculation (EGR) (Chatterjee et al, 2003) for NOX control, and diesel particulate filters to reduce solid fraction emissions.

The following sections concentrate on the use of exhaust particulate filters since these are expected to be the technology that will provide the most substantial PM reduction. It is expected that PM filters will be used in conjunction with NOX in-cylinder and aftertreatment technologies to achieve the emission levels required by legislation.
1.5 **Diesel Particulate Filters (DPF)**

Particulate filters are available in many forms including ceramic foams, fibre filters and sintered metals, but the current standard is a ceramic monolith consisting of small longitudinal channels which are alternately blocked by small ceramic plugs at inlet and outlet ends. The exhaust gas is forced to pass through the porous wall of the channel, which filters the particulates from the gas flow as illustrated in Figure 1-5.

![Diagram of Exhaust Flow through a Wall Flow Diesel Particulate Filter](image)

**Figure 1-5 - Exhaust flow through a wall flow diesel particulate filter (Tan et al, 1996)**

The filter restricts flow thus increases the engine exhaust flow back pressure. As the filter loads with PM this back pressure increases, to the detriment of engine performance and fuel economy. Therefore, the increase in back pressure must be minimised by periodically or continuously cleaning the filter, allowing the same filter to continue to trap PM from the exhaust gases. This cleaning process is called regeneration.

Regeneration is essentially a problem of removing the primarily carbonaceous PM from a filtration surface (see Figure 1-6) and disposing of it usually through oxidation to CO₂. The ignition temperature of diesel PM is approximately 550 °C, a temperature rarely reached by diesel exhaust gas under normal engine operation in many applications. Thus the oxidation process needs to be assisted either by:
1. lowering the ignition temperature of the trapped matter using reaction catalysts;
2. increasing the temperature of the trapped PM to above 550 °C.

Figure 1-6 - Carbonaceous PM trapped by the porous ceramic filter media (Mayer, 1999)

Most regeneration systems seek to oxidise the PM on the filtration surface, since removal prior to oxidation has proved difficult to accomplish. However, allowing the exothermic oxidation reaction to occur on the filter surface introduces the risk of thermally damaging the filter, thus the process must be controlled carefully.

The research findings of a large number of filter regeneration systems have been published since the early 1980's, some of which are discussed in Chapter 2. Common problems reported with filter regeneration systems include:

1. high energy requirements during regeneration system operation increasing engine fuel consumption;
2. rapid uncontrolled regeneration leading to high heat release rates from the oxidising PM and therefore high thermal gradients within the filter substrate, causing damage;
3. high minimum filter loading requirement for complete regeneration to be achieved and the subsequent risk of uncontrolled combustion causing filter damage (by cracking or melting);
4. ash accumulation within the filter from incombustible fuel additives and regeneration catalysts;
5. low sulphur fuel requirement to prevent exhaust catalyst poisoning or increased sulphate emissions;
6. requirement to bypass the filter during regeneration to prevent convective heat losses extinguishing regeneration; and the
7. requirement to supply significant volumetric flowrates of secondary air to sustain PM oxidation.

These problems have meant that few systems have made the significant step into series production, the Peugeot cerium based fuel additive and the Johnson Matthey Continuously Regenerating Trap (CRT) being the notable exceptions. However, even these systems have significant drawbacks such as their susceptibility to sulphur within the fuel which can lead to excessive sulphate emissions and the service requirements to maintain cerium levels and remove additive derived incombustible ash from the filter.

1.6 Introduction to the Autoselective Regeneration System

The new regeneration method that is the subject of the research reported in this thesis utilises high frequency alternating voltage electrical discharges to generate plasma. These discharges were shown to successfully oxidise diesel PM in a feasibility study conducted at Loughborough University by the inventors J E Harry and C P Garner (1998). The study demonstrated that a single pin electrode generating a ‘cold plasma’ through electrical discharges caused the oxidation of diesel PM in still air, at atmospheric temperature and pressure, and consumed approximately 20 W of power. The system was believed to be capable of regenerating filters with very low mass loadings relative to other systems in published research. Thus the low energy consumption and the ability to operate at low mass loadings provide the system with the potential to reduce the impact of PM aftertreatment on-engine fuel economy and performance.
The potential advantages brought to light by the early work on this system were:

1. the low power consumption, minimising the impact on-engine fuel economy of operating the regeneration system;
2. regeneration at relatively low filter loadings, minimising the increased fuel consumption from elevated exhaust back pressure and minimising the chance of thermal runaway during regeneration of heavily loaded filters;
3. the system requires no catalyst to be introduced to either the fuel or filter monolith;
4. the system performance is not affected by the sulphur content of the fuel; and
5. the system is inherently Autoselective. When PM is present the discharge activates automatically. Thus no control system is required to initiate regeneration or to control regeneration once it has begun.

1.6.1 Novelty of the Autoselective Regeneration System

AEA Technology (MacAdams, 2001) and Atmospheric Glow Technologies (Kelly et al, 2003), amongst others, have reported regeneration systems that utilise some form of plasma discharge. However, these systems have completely different modes of operation from that researched by this work. The AEA system used a low temperature plasma to produce a reaction that converts NO to NO\(_2\), which subsequently oxidised the PM. The Atmospheric Glow Technologies system used an audio frequency discharge which was believed to bare closest relation to a dielectric barrier discharge (DBD) type plasma. The plasma generated highly reactive chemical species near the filter that then oxidise the PM. The Autoselective System, however, uses the hot root of a cold plasma discharge to rapidly heat the trapped PM above the ignition temperature of 550°C, thus causing local oxidation.

The relatively low power consumption of the Autoselective System is believed to stem from its use of energy to treat the solid PM directly, not the complete exhaust
gas flow or any attempt to heat the filter monolith above the PM ignition temperature. The system does not attempt to initiate a self-sustained regeneration and thus does not require a critical mass of PM. The filter can potentially be kept effectively clean or at very low loading. This benefits engine performance by reducing the exhaust backpressure thus improving fuel economy. The reduced loading during regeneration also removes the risk of the exothermic oxidation reaction becoming uncontrolled and melting the filter monolith. The lack of a minimum loading requirement before regeneration can be performed may also allow the filter monolith size to be reduced, enabling improvements in filter mechanical durability and packaging within the vehicle.

1.6.2 Requirement for Autoselective Regeneration System Research

The early Autoselective System feasibility study showed the system to have a number of potential advantages over other regeneration systems discussed in published research. However, the early study did not show that the system was capable of operating within a diesel engine exhaust nor how effectively it could operate under such conditions. The key variables that controlled performance had not been identified. Therefore, the research detailed in this thesis aimed to answer these important questions.

1.7 Thesis Overview

Chapter 1 has so far described the formation of PM and the potential health affects that have driven the introduction of increasingly stringent emission legislation. The different emission abatement techniques were then briefly described along with the issues involved with simultaneous NO\textsubscript{x} and PM reduction. The likely requirement of diesel particulate filters was established along with their requirement for regeneration. Some of the issues reported with filter regeneration are listed which highlights the requirement for further work in this area, specifically the work to research the Autoselective regeneration system which is the subject of this thesis.
Chapter 2 introduces details of diesel particulate control using ceramic filtration elements and their requirement for regeneration. Various previously reported techniques for regeneration of diesel particulate filters are then detailed including thermal regeneration, catalytic regeneration and introducing regeneration using electrical discharge plasma.

Chapter 3 initially discusses the fundamental aspects of plasmas generated by electrical discharges in gases. The subsequent sections discuss the various types of plasma that can be generated at atmospheric pressure and their applications. The final section then discusses regeneration systems that use electrical discharge plasma to provide controllable regeneration. The advantages of electrical discharge systems are highlighted alongside the limitations of many of these systems, including relatively low oxidation rates.

Chapter 4 discusses a hot flow rig which simulated the major characteristics of the diesel engine exhaust gas flow environment. The rig provided a controlled environment in which the operation of the Autoselective discharge could be investigated. The techniques used to assess wall flow filter loading and regeneration effectiveness are then discussed. The experimental procedures are detailed including an introduction to the Design of Experiments (DoE) techniques used to reduce the number of experiments required to more fully investigate the Autoselective system performance.

Chapter 5 reviews the investigation of the fundamental characteristics of the Autoselective discharge, such as discharge regime and alternating frequency, and their influence on filter regeneration performance. The performance of the discharge in exhaust like flows is then detailed along with a quantified investigation of the affects of the various flow characteristics on discharge power and regeneration rate. These preliminary investigations provided the basis for the development of a electrode configuration to use the Autoselective discharge to regenerate the full volume of a diesel particulate filter.
Chapter 6 describes the development and investigation of an inserted electrode configuration. The first sections detail the investigation of the variables within the electrode configuration, such as electrode spacing, and the preliminary examinations of the regenerated filter. The requirement for power modulation is discussed and the optimisation of a duty cycle is detailed. The final sections describe a DoE investigation of the discharge power and regeneration performance of the prototype electrode configuration within the hot flow rig.

Chapter 7 describes more detailed investigation of the performance of the inserted electrode Autoselective system including assessment of the gaseous by products of regeneration. Novel experimental techniques were developed and used to assess time based trends within the regeneration process. The following section then discusses the testing of the prototype regeneration system on a dynamometer loaded engine and shows that the test results validate those gathered through hot flow rig testing. The final section provides a summarised comparison of the various regeneration systems discussed in Chapter 2 with the developed Autoselective system prototype.

Chapter 8 details the major conclusions of this thesis and outlines potential areas for future work.

The Appendices of the thesis are included to provide the DoE statistical analysis and diagnostic data which validates the use of the experimental data for analysis of the Autoselective discharge and system performance. The analysis of the Autoselective discharge power and regeneration rate performance is provided in Chapter 5 and Chapter 6.
1.8 **Contributions to Knowledge**

The work detailed in this thesis has made a number of novel key contributions towards the investigation and development of a diesel particulate filter regeneration system using the Autoselective discharge. These were:

1. The development of an apparatus to study the Autoselective discharge performance under controlled conditions, which simulated those within a diesel engine exhaust.
2. Investigation of the fundamental characteristics of the Autoselective electrical discharge and their influence on regeneration performance allowing specification of the optimal electrical characteristics.
3. Investigation of the Autoselective discharge behaviour in gas flow conditions similar to those within a diesel engine exhaust.
4. Development of a prototype system using the Autoselective discharge that regenerated a standard wall flow filter in exhaust conditions.
5. Validation of the performance results gathered through hot flow rig investigations by testing the prototype system on a dynamometer loaded engine.

1.8.1 **Publications from this Research**

A US and European patent has been granted and a further series of patents are currently being filed that encompass a significant number of valuable innovations, including electrode configuration and power supply that have resulted from the work discussed in this thesis. Due to the novel and confidential nature of the work conducted it was not considered prudent to publish papers directly on the regeneration system or its performance results until all necessary patents are filed. However, two journal papers and a conference paper were published in the related
field of electrical discharge structure and behaviour in atmospheric pressure air. The papers were published in addition to a patent that extended the work covered in the original applications. The publications are:


This chapter introduces the diesel particulate filter, which is widely accepted as a required control measure for PM emission reduction for heavy-duty diesel Euro V legislation, to begin introduction in 2008 (dieselnet.com, 2005). The filter structure and filtration mechanism is initially described, concentrating on the Cordierite wall-flow filters that were used for the majority of the research that is the subject of this thesis. The issues encountered in regenerating diesel filters such as determining when regeneration is required and how to control the process is then discussed. The majority of this chapter then describes a number of specific examples of the various types of regeneration concept that have been reported in published research along with analysis of the strengths and weaknesses of each regeneration method.
Chapter 2 - Diesel Particulate Filter Systems and Regeneration Methods

2.1 Diesel Particulate Filters

The most effective method of reducing diesel particulate emissions is to use a diesel particulate filter within the exhaust system. Filters are generally classified according to their operating principle. Deep bed filters are normally ceramic or metal foams, wire mesh or ceramic wool, and act in a three dimensional manner with PM accumulating throughout the filter. Shallow bed filters follow the wall-flow concept, typically ceramic monoliths that force exhaust gases to pass through thin porous walls between channels with alternately blocked inlets and outlets (see Figure 2-1). The filtering process is described as essentially two-dimensional with PM collecting only on the upstream wall surface.

![Figure 2-1 - Shallow bed wall flow filter (Johnson, 2005)](image)

2.1.1 Filtration Mechanisms and Efficiency

Filters do not only filter suspended particles with larger diameter than the pores in their structure through interception. Important processes such as diffusion, thermophoresis and inertial impaction also occur (Davis, 1973). These processes are particularly important in deep bed filters because the distance between fibres or the macro porosity of the filter is much larger than particle diameter. This large macro porosity can also allow filtered PM to be released or blown through the filter under high gas flow rates, a problem not associated with wall-flow filters. Overall, deep bed filters tend to be less efficient at filtering PM entrained in the exhaust gas flow.
than wall flow filters. Deep bed filters exhibit a filtration efficiency of 60 – 70% on a mass basis compared to > 90% for wall-flow filters.

The high filtration efficiency is the main reason why wall-flow filters are expected to be the standard choice to meet the Euro V emission legislation. Therefore, much of the regeneration system research published to date has concentrated on the use of wall-flow filters, as will the research discussed in the later chapters of this thesis. However, the potential packaging and cost advantages of deep bed filters means that their research and development has continued and they may be used in some applications.

2.1.2 Filter Design

Filter design is a compromise between the requirements of high filtration efficiency and low backpressure imposed by the system. A filter is essentially a restriction to the flow of exhaust gas and this restriction increases as PM is accumulated within the filter. Increased backpressure is detrimental to engine performance and fuel economy. Generally, a high filtration efficiency filter will remove substantial amounts of PM but will impose a high backpressure on the engine, which reduces engine fuel economy.

The current automotive standard is the wall-flow filter manufactured from Cordierite or Silicon Carbide (SiC). Cordierite offers good filtration efficiency of 90-95%, but relatively poor thermal and mechanical properties compared to SiC. However, SiC is conductive and as such the filter monolith would provide a permanent ground site for an electric discharge such as the Autoselective discharge that will be described later in this thesis. The discharge would operate continuously and therefore eliminate the benefits of the Autoselective characteristic, thus the system is only used with the Cordierite wall flow filter in this research.
PM accumulates in a dense layer on the ceramic wall as the exhaust gases pass through the filter. Oxidation of this layer during filter regeneration is a highly exothermic reaction. The low thermal conductivity of Cordierite prevents dissipation of the energy released during oxidation and allows high temperature regions to develop to the extent where filter melting can occur. The high temperature regions also produce thermal gradients across the filter that stress the monolith and can initiate cracking. SiC has a significantly higher thermal conductivity (Gantawar et al, 1997). This allows the exothermic energy from oxidation to be dissipated within the wall-flow filter, minimising both the peak temperatures and the thermal gradients.

Deep bed filters are less prone to thermal damage during regeneration since the PM is less densely packed, thus the oxidation reactions in such filters are often not self-sustaining and will generally only proceed as long as energy is supplied from an external source.

2.2 Wall-flow Diesel Filter Characteristics

Filtration efficiency and filter pressure characteristics are determined by filter geometry, size, volume and wall thickness and also by the material properties of the filter, such as porosity and pore size distribution (Stobbe et al, 1996, Murtagh et al, 1994, Uchiyama et al, 1994). Small pore size provides high filtration efficiency but increased backpressure. However, at high loadings these relationships change. The filter pores eventually fill, leading to a layer or 'membrane' of PM forming on the wall. This membrane modifies and eventually dominates the filtration and backpressure characteristics.

The accumulation of PM, known as loading or fouling rate, influences the pressure drop and filtration characteristics, and how they change with time (see Figure 2-2).
Chapter 2 - Diesel Particulate Filter Systems and Regeneration Methods

Figure 2-2 - Filter loading or fouling of Cordierite monolithic wall flow filters (a) Pressure drop; (b) Filtration efficiency. [Filter details: mean pore size (µm), porosity (%): EX-47 (13.4, 50); EX-54 (24.4, 50); EX-66 (34.1, 50); EX-80 (12.5, 48)]

(Adapted from Murtagh et al, 1994)

All of the filters in Figure 2-2 above have very similar geometry and porosity, the differences are accounted for by the ceramic wall pore size. The key feature is the change in the rate of increase of pressure drop and the filtration efficiency. Initially, the pressure drop and its rate of change are higher for small pore filters (EX-80 and EX-47). However, eventually the rate of increase of pressure drop for all filters becomes the same, and filtration efficiency becomes a much weaker function of loading. This is due to the formation of the PM membrane over the filter wall causing filters with different pore size to develop the same filtration efficiency. Large pore filters eventually develop higher backpressure as the pores themselves become blocked, not merely covered, as is the case for small pore filters. The build up of PM actually within the larger pores provides a more effective flow restriction and in turn leads to relatively larger pressure drops across loaded large pore filters (Murtagh et al, 1994).

These filter loading results affect the filter specification due to the affects on engine fuel economy. Figure 2-2 demonstrates that for the same backpressure, small pore filters can accumulate more PM than large pore filters, and thus will require less frequent regeneration. The less frequent regeneration is required, the smaller the total energy requirement. However, the larger the mass of PM within the filter
during regeneration, the greater the chance of the exothermic regeneration processes becoming aggressively self-sustained and possibly damaging the filter thermally. This argument only holds if the original pressure drop caused by the unloaded filter is acceptable. If the original backpressure from small pore filters causes severe detriment to engine fuel economy, large pore filters will be employed with frequent regeneration to maintain adequate engine operation.

2.3 Practical Issues Involved With Particulate Filtration and Oxidation

To oxidise the carbonaceous component of the PM, it must be supplied with sufficient energy to reach the ignition temperature. Large variations in PM physical structure (e.g. density and size distribution) and chemically (e.g. absorbed hydrocarbons) mean there is no definitive ignition temperature, but accepted values are between 550 °C and 600 °C. Typical diesel engine exhaust temperatures are in the range 200 °C to 500 °C, with only occasional excursions above 550 °C. Studies of driving patterns for urban buses and urban use lorries showed that exhaust temperatures of 500 °C were only achieved for two seconds every ten minutes (Suto et al, 1992). Passenger car exhaust temperatures have been observed not to rise above 250 °C during urban driving, and not above 400 °C for extra urban driving (Adams et al, 1996).

The specific power of diesel engines is often increased through the use of a turbocharger, however, they reduce the post turbine exhaust gas temperature. The particulate filter may be positioned closer to the engine, possibly before the turbine, but the poor thermal durability of Cordierite can cause the filter to fracture and allow ceramic fragments to pass through the turbocharger turbine causing damage. Thermally robust filter materials such as silicon carbide may alleviate this problem, but the filter upstream of the turbocharger will increase the turbocharger speed and boost lag, reducing driveability. Pre-turbocharger turbine filter systems have been designed and found to have beneficial thermodynamics for PM oxidisation. The
position also facilitates routing of the Exhaust Gas Recirculation (EGR) from the filtered gases, avoiding problems of PM re-entering the engine and becoming entrained in lubricant oil and increasing engine wear (Psaras et al, 1997).

PM oxidation, or filter regeneration, can occur naturally if the duty cycle produces the required high exhaust gas temperatures with sufficient frequency. However, in most applications some external intervention is required.

Numerous regeneration methods have been proposed, and they can generally be divided into two groups depending upon their primary goal:

1. Catalytic systems seek to reduce the temperature at which the oxidation reaction occurs, thus making the exhaust gas temperature potentially sufficient to initiate regeneration.
2. Thermal systems aim to input the energy required to raise the PM temperature above the natural ignition temperature of 550 °C.

Within both of these groups a number of different systems have been proposed and researched. However, a number of general concerns, such as minimising the thermal loading of the filter, must be addressed by all filter regeneration systems and strategies.

The durability of a filter is strongly dependent upon both the peak temperature that occurs during regeneration and the temperature gradients within the filter (Hoj et al, 1995). The low thermal conductivity of Cordierite allows high temperature regions to develop. The temperature gradients and the thermal cycles determine the fatigue life of the filter. High peak temperatures are avoided by initiating regeneration at low filter PM mass loadings, thus minimising the exothermic energy release during oxidation. Preventing temperature gradients is more difficult as these often occur during partial regenerations (MacDonald and Simon, 1988). The vulnerability of Cordierite filters to thermal damage requires the regeneration process to be monitored or carefully controlled.
2.3.1 Filter Loading Assessment

Exhaust gas backpressure is the most practical indicator to monitor the regeneration requirement, progress and effectiveness, especially since it is backpressure that is the target variable for reduction through filter regeneration. Precise determination of backpressure is difficult under real driving conditions, since it is a function of exhaust gas flow rate. Control systems have been developed that monitor engine speed and turbocharger boost to account for changes in gas flow rate when determining filter pressure drop (MacDonald and Simon, 1988).

2.3.2 Regeneration Monitoring

If the backpressure across the filter becomes constant during regeneration, PM enters the filter at the same rate as oxidation is occurring. More usually, the backpressure falls rapidly during regeneration. Regeneration systems reliant on elevated gas temperatures during particular driving cycles, such as catalytic systems, provide no control of the conditions under which oxidation occurs. Fluctuations in duty cycle can prematurely terminate regeneration preventing the backpressure falling to the clean filter baseline. Thermal regeneration methods should ideally return the backpressure to the base line level if performed correctly.

Regeneration monitoring via temperature measurements is subject to significant problems. If regeneration is localised then thermocouples within the filter will not provide accurate data when they are distant from the oxidation region. Comparison of gas temperatures at filter outlet and inlet provides an indication that regeneration is occurring, however it is not sensitive enough for accurate monitoring (Pattas and Stamatelos, 1991). Even if it does detect a large filter temperature excursion during regeneration, the regeneration process can not be easily controlled fast enough to prevent filter damage by melting or cracking.
The above discussion shows that precise assessment of regeneration requirement and progress is difficult to achieve through the monitoring of exhaust gas characteristics near the filter. An ideal regeneration system should, therefore, be capable of providing a controlled regeneration under all conditions experienced within the diesel exhaust system.

2.3.3 Incombustible Ash

Incombustible materials from the fuel and oil gradually leads to an accumulation of ash within the filter, which tends to raise the baseline backpressure and reduce the PM loading prior to regeneration. The frequency of regeneration must therefore increase, which has a detrimental effect on regeneration system energy requirements and filter durability. Ash originates from incombustible elements within the fuel and oil. Chemical analysis has identified compounds such as calcium sulphate, zinc magnesium phosphate, zinc phosphate and manganese oxide. The first compound reduces significantly if low sulphur fuel is adopted. Another significant source of ash is engine performance enhancing fuel additives and fuel borne regeneration catalysts.

Ash tends to form highly porous structures (Rao et al, 1994) that do not always lead to a rise in the backpressure across the filter but do reduce the PM accumulation capacity. Ash particles are more dense and larger than exhaust particulates, thus they tend to accumulate towards the downstream end of wall-flow filter channels. Apart from the modifications to pressure and flow characteristics, ash can affect filter structure. Molecular interactions between Cordierite and sodium or iron can occur at temperatures of approximately 700 °C, causing filter monolith embrittlement and increasing the vulnerability to damage from thermal shocks and gradients (Montanaro and Negro, 1998).
2.4 Diesel Particulate Filter Regeneration Systems

A regeneration system must not only operate to adequately clean the filter in such a way as not to cause thermal damage, it must also address the issues that are associated with all on-engine systems. These issues include minimal cost, simple packaging, adequate durability, long service intervals and minimal impact on engine fuel economy.

The energy required for filter regeneration can be minimised if the energy within the hot exhaust gas is used. However, as explained earlier, the natural ignition temperature of the PM is higher than that usually reached by diesel engine exhaust gas during normal engine operation. If the ignition temperature of the PM were to be reduced then the heat energy within exhaust gases may be used, thus minimising the impact on fuel economy.

2.5 Catalytic Filter Regeneration

Catalysts are used to reduce the ignition temperature of filtered PM, below the normal 550 °C, to where the heat within the exhaust gases is more frequently sufficient to cause oxidation (Ciambelli et al, 1996). This is sometimes referred to as 'passive regeneration' with no external energy source used to initiate or control oxidation, thus removing reliability problems associated with such sub-systems. An ideal catalyst would reduce the ignition temperature to the extent where regeneration is continuously in operation, never allowing the filter to become loaded. However, this ideal has not yet been achieved, thus the regeneration frequency depends on how regularly the engine duty cycle produces the correct exhaust conditions for regeneration to be initiated. The frequency with which these conditions are achieved determines the filter loading prior to regeneration. Since filter loading prior to regeneration is not under direct control, peak temperature experienced during regeneration is not controlled since a greater mass of PM releases more energy during oxidation. The combustion process in heavily loaded
filters can become self-sustaining, possibly leading to thermal runaway. To prevent such high loading conditions some catalytic systems have a back up regeneration method such as exhaust gas throttling, which is discussed later in this chapter, or protection systems such as a filter bypass.

The catalytic reduction in ignition temperature can be influenced significantly by a variety of factors. An oxidation catalyst is more effective in high oxygen conditions. \( \text{NO}_x \) concentration has been reported to be also influential (Jelles et al, 1999) and fuel derived sulphur is known to interfere with catalysis. Engine type and duty cycle account for differences in PM characteristics such as ash content, hydrogen to carbon ratio, particle geometry, soluble organic fraction and the conditions to which the filtered matter has been exposed to prior to oxidation. All of these factors can then account for differences in ignition temperature and the unpredictability of catalytic regenerations.

Partial regenerations are common, especially at lower exhaust gas temperatures. Localised areas of the filter are regenerated, providing a preferred flow path for the exhaust gas. These high flow regions undergo increased convective cooling often extinguishing the particulate oxidation.

Catalyst systems can be designed to prevent high loadings, with filter size and position especially influential. The size of the filter affects the clean condition backpressure and the rate of increase of backpressure as loading occurs. Hence, the filter size in part determines the regeneration frequency but not the backpressure at which regeneration is initiated. The critical backpressure is in part determined by filter position, or distance from the engine. Positioning a filter further downstream in the exhaust system causes the exhaust gases to cool before reaching the filter. Since catalyst systems require a given exhaust gas temperature to initiate regeneration, the likelihood of this temperature being achieved at the filter is diminished by its distance from the engine. Thus exhaust backpressure will continue to build until it is such that the exhaust temperature is elevated by the throttling effect on the engine and eventually the gas temperature at the filter is sufficient to
cause regeneration. Large filters, positioned away from the engine will develop high loadings as the gas temperature are relatively low, however, they will then experience high temperatures during regeneration, increasing the possibility of thermal damage. Small filters positioned close to the engine will regenerate much more frequently, but this then introduces thermal fatigue problems. Catalytic systems do still produce a fuel economy penalty due to the increased exhaust backpressure caused by the filter and its particulate loading. The engine duty cycle determines the regularity of regeneration, and thus the fuel economy penalty introduced for a particular application. Low engine speed operation allows larger particulate loadings to develop, with a measurable increase in fuel consumption, but high engine load operation provides regular regeneration with relatively little influence on fuel economy (Pattas et al., 1997). Thus an optimum catalytic system design, regarding filter size, position and catalyst specification, depends upon the duty cycle of the engine when considering fuel economy and system durability.

2.5.1 Fuel Borne Catalysts

Fuel borne catalysts are usually trace amounts of metallic compounds, which are oxidised in the combustion chamber (Farrauto et al., 1993). These metal oxide particles become incorporated into the PM, producing a catalytic effect that allows low temperature oxidation within the filter. Fuel borne catalysts include copper, cerium, iron, sodium, lithium and combinations of metals such as strontium and iron (Clerc, 1996).

The amount of additive introduced determines how frequently regeneration will occur for a particular application and system. Passenger cars have a cerium additive dosage of 200 ppm, whereas a public transport bus application only requires 100 ppm (Pattas et al., 1996); however further research has aimed to reduce these levels. The difference in dosage is due to the bus duty cycle raising the exhaust peak temperature higher and more frequently than the passenger car; therefore, the bus PM ignition temperature does not need to be lowered to as great an extent.
Additives have been observed to lower the mass of engine-out PM (Zelenka et al., 1998). The reduction was explained by an increase in beneficial deposits within the combustion chambers of the engine. Neither the exact nature of these deposits nor their effects were detailed further. Further research may indicate that the nature of the PM production has been altered by the presence of cerium. Increased nanoparticle levels have been reported, with the increased nano-particle fraction corresponding to increasing cerium dosage (Mayer et al., 2002).

Several concerns surrounding catalytic fuel additives, such as additive delivery, have to be adequately addressed. An additive that is supplied pre-mixed within the fuel must be stable for long periods and not separate or precipitate out of suspension. An alternative method of additive delivery is to supply it from separate reservoirs on the vehicle, but this adds extra service requirements which vehicle manufacturers (both passenger car and heavy duty) are reluctant to accept. A solid catalyst, which sublimes under heating, and is then entrained into the intake air has been investigated, but dosage control proved problematic (Bloom et al., 1997).

There are a number of other concerns regarding fuel additives. There may be a danger of accelerated engine wear if the additive derived particles enter the engine lubricant, and the formation of deposits in the combustion chamber or fuel injectors may cause increases in other emissions. Possibly more critically, although their short-term toxicity is low, the long-term health effects of a number of fuel additives including cerium are not known. Inhalation of nano-particles is believed to be the most common route for fuel additive chemicals to enter the body, and once present can affect the respiratory tract and lymph nodes. Animal studies have indicated large doses of cerium can cause neurological effects and long-term human exposure to cerium has been correlated with a condition similar to asbestosis called ‘rare earth pneumoconiosis’ (California Environmental Protection Agency, 2005). The exact role of cerium in the condition is not known and the results to date may be confounded with other metal aerosols. The required dosages are not detailed in the published research (Mayer, 1998, Mayer, 1999). Further research into the long-term affects of
cerium and other additives such as iron and copper aerosol are required to ensure the dangers of diesel PM are not replaced with the dangers of fuel additive aerosols.

The largest known problem associated with fuel additive catalysts is the build up of incombustible ash material within the particulate filter as a result of the metal oxide additives after regeneration. This ash not only increases the clean filter backpressure but it can react with the filter material at high temperatures, leading to embrittlement of the ceramic monolith. Cerium has been found to be safe with Cordierite filters and even reported to have some beneficial effect in modifying the porosity of metallic filters (Montanaro and Negro, 1998), but still produces significant ash deposits that must be dealt with during vehicle service. Iron is detrimental to metallic filters and copper oxide ash build up in fibre filters has limited service life to around 24,000 kilometres (Bloom et al, 1997). However, different fuel additives produce different amounts and types of ash, which result in different backpressure changes across the filter. Ash from iron and cerium additives was not found to produce high back pressure and shorten filter life, but copper additives initiated such high oxidation rates that thermal damage was regularly caused to fibre filters (Bloom et al, 1997). Current research has concentrated on modifying and combining additives, such as cerium and iron, in order to minimise dosage requirements and thus minimise ash build up (Seguelong et al, 2002, Blanchard et al, 2003).

Different fuel additives have been found to have different regeneration characteristics. At higher gas temperatures, copper, cerium and iron have been shown to cause continuous regeneration. At exhaust temperatures below 400 °C, copper and iron additives can produce very rapid regeneration, inducing backpressure profiles that rise linearly with time and then rapidly fall. This style of regeneration produces high temperature gradients that are detrimental to filter durability. Cerium additives produce more regular, low oxidation rate regenerations, but which may not be complete, thus the fuel economy penalty of cerium additives can be greater as the back pressure across the filter is generally higher.
2.5.2 Catalysed Filters

Catalysed filters comprise a filter monolith with a catalyst applied directly, not in a wash coat as with automotive catalytic converters. Wash coats tend to increase the backpressure across conventional wall-flow filters thus are generally avoided. The major problem associated with catalysed filters is ensuring contact between the PM, the catalyst and oxygen within the exhaust gas (Fino et al, 2003). Fuel additives have the advantage of being part of the PM thus ensuring contact. Catalysed filters can become covered with incombustible material preventing contact between the combustible PM and the catalyst. A large number of metal oxide catalysts, such as Cobalt Oxide (Co$_3$O$_4$), are effective in close contact with PM, but lose the catalytic effect once contact is lost. Engine tests have shown the problem of contact is less pronounced during the oxidation of the soluble organic fraction, which often exists in the gas phase. The oxidation of the soluble organic fraction generates heat, which can then lead to partial oxidation of the solid carbon component within the filter.

The ignition temperature of the PM is only reduced to around 400°C with most catalysed filters, insufficient for most applications. Thus many systems incorporate external energy sources and the catalyst only acts to reduce the required energy input to initiate oxidation. However, sustained or complete regeneration has not been found in all tests of catalysed filter systems (Ha et al, 1991). This may be because when regeneration occurs in a catalysed filter, the soluble organic fraction has often already been oxidised, so less exothermic energy is available to sustain the regeneration reaction.

Deep bed ceramic fibre filters have been catalysed for regeneration. A Vanadium based catalyst (V$_2$O$_5$) can reduce PM ignition temperature to 350 °C (Mayer et al, 1996). However, the catalyst was broken down to inactive V$_2$O$_4$ and V$_2$O$_3$, at temperatures above 650 °C. This means V$_2$O$_5$ could not applied to the higher filtration efficiency Cordierite wall-flow filters due to its tendency to experience local high temperature regions during even mild regenerations.
2.5.3 Oxidation Using NO\textsubscript{2}

Research on diesel oxidising catalysts in the late 1980’s indicated that oxygen was not the only exhaust gas constituent that is capable of oxidising carbon. The reaction rate of oxygen and carbon with oxidising catalysts could not account for the carbon dioxide levels measured during experiments (Cooper and Thoss, 1989).

Investigations found that carbon oxidation ceased when nitrogen oxides were removed from the feed gas to the catalyst, even when oxygen was still present, but continued when NO\textsubscript{2} was introduced. Platinum catalysts are active in the conversion of NO to NO\textsubscript{2} in typical diesel exhaust temperatures. Thus, NO is oxidised to NO\textsubscript{2}:

\[2\text{NO} + \text{O}_2 \rightarrow 2\text{NO}_2\]

and

\[4\text{NO} \rightarrow \text{NO}_2 + \text{N}_2\]

The NO\textsubscript{2} then oxidises the carbon:

\[\text{NO}_2 + \text{C} \rightarrow \text{NO} + \text{CO}\]

and

\[\text{CO} + \text{NO}_2 \rightarrow \text{CO}_2 + \text{NO}\]

The problem of ensuring catalyst-carbon contact that inhibits the effectiveness of catalytic monolith systems is avoided. The platinum catalyst is active on the gas phase NO, producing NO\textsubscript{2}; the NO\textsubscript{2} gas constituent then travels to the filter where particulate oxidation occurs.

This concept was developed into the Johnson Matthey Continuously Regenerating Trap (CRT) (Hawker, 1995), using a precious metal oxidation catalyst upstream of a wall-flow particulate filter (see Figure 2-3). Continuous regeneration has been reported above 275 °C.
The device was tested successfully in a field trial on trucks and buses. The system was also found to reduce hydrocarbon (HC), carbon monoxide (CO), soluble organic fraction (SOF), aldehydes and Polycyclic Aromatic Hydrocarbon (PAH) fractions within the exhaust (Hawker et al, 1997), although reduction mechanisms and performance details were not reported.

The effectiveness of the CRT system is influenced by the exhaust gas NO\textsubscript{x}/C ratio and somewhat by the exhaust temperature. At NO\textsubscript{x}/C ratios below 8, independent of temperature, the system was not capable of continuous regeneration (Zelenka et al, 1998). The minimum ratio was found to be dependent on exhaust gas temperature, where higher NO\textsubscript{x}/C ratios are required for lower temperature applications (Fleetguard, 2004). Exhaust gas NO\textsubscript{x} concentration must be monitored, with the potential requirement to reduce the Exhaust Gas Recirculation (EGR) rate to raise the engine-out NO\textsubscript{x} emissions. The catalyst that oxidises NO to NO\textsubscript{2} only becomes active above 200°C and is then limited above 350 °C (see Figure 2-4) (Harkonen et al, 1994). The narrow operational temperature range of the system can make regeneration intermittent on some drive cycles. This leads to increasing exhaust backpressure causing increased levels of engine-out PM and reduced levels of engine-out NO\textsubscript{x}, thus limiting regeneration effectiveness even when the correct gas temperature is attained (Hawker et al, 1997).
The CRT system, similar to other oxidation catalysts for diesel aftertreatment is susceptible to sulphur within the fuel. Absorption of the engine-out sulphur dioxide into the catalyst prevents the absorption of NO, thus stopping the formation of NO₂. Moreover, oxidation catalysts will convert sulphur dioxide (SO₂) to SO₃. This combines with water to produce sulphate particulates (e.g. H₂SO₄), 'increasing' the total mass of the emitted tail-pipe PM. The sulphate conversion is highly temperature dependent. A critical temperature, at which the mass of sulphate particulate produced is equal to the mass of carbon being oxidised, lies within typical exhaust temperatures. Thus, the CRT system should only be used where the fuel sulphur content is below 10 ppm (Hawker et al., 1997). Fuel sulphur levels up to 500 ppm can be accommodated, but a different catalyst must be used which requires higher gas temperatures and is less effective in promoting regeneration (Fleetguard, 2004). Fuel sulphur content varies between countries, thus potential use of the CRT system is currently limited.

The oxidation catalyst of the CRT system can be platinum or platinum-rhodium. Platinum-rhodium forms fewer sulphates than platinum alone, however, platinum has a lower light-off temperature. Platinum catalysts show an increase in sulphate particulate emission with use, caused by an eventual saturation and breakdown of a sulphur storage capacity within the catalyst (Cooper and Thoss, 1989). Further investigations into lowering the regeneration temperature of the system have shown...
direct relation to the critical temperature at which sulphate particulate emissions equal the oxidation rate of the carbon particulate. Thus, low regeneration temperatures can only be achieved by using catalysts that have low critical temperatures (Cooper and Thoss, 1989), reinforcing the need for low sulphur fuels.

The CRT system is arguably the most widely applied PM filter regeneration system in production at present with numerous retrofit applications on city buses and state service lorries in the US. (Chatterjee et al, 2002, Allansson et al, 2002)

2.6 Thermal Regeneration Systems

Catalytic systems are desirable due their minimal fuel penalty. However, the PM ignition temperature can still be too high to achieve continuous regeneration under most duty cycles.

Thermal regeneration systems provide energy from an external source to initiate and possibly maintain particulate oxidation. These are active systems where regeneration is initiated by some control function based on filter loading and is not directly dependent of engine operating cycle or exhaust gas temperature. The most common parameter used to assess particulate loading is the filter backpressure (see Regeneration Monitoring section of Chapter 2). Some systems used on engines with repeating operating cycles, such as power generators or buses operating the same route, use open loop control, where regeneration is initiated regularly after a set period of operation (Kumagai et al, 1996). Most engines do not operate on such predictable cycles. The most important design aim is then to minimise the energy requirement thereby minimising the impact on fuel economy. The regeneration process must be efficient and the duration and frequency of the regenerations must be optimised carefully.

A range of factors influences the fuel economy impact of thermal regeneration systems. The fuel required for the burner, the fuel consumed by the engine to power
the alternators for electrical heating, energy required by ancillary equipment such as secondary air blowers, and the effectiveness with which heat energy is transferred to the filtered particulate are all important. Gas temperature, oxygen content and flow rate must be carefully monitored, not only to prevent rapid regenerations which can cause high heat release rates and thermal damage to the filter, but also since these factors influence the energy input required for regeneration. These factors are closely related. For example, the injection of secondary air can cool the exhaust gases but enhances combustion due to the additional oxygen supplied, whilst at the same time it increases heat lost to convection from the filter.

A further contribution to the fuel economy penalty comes from the increased back pressure caused by the simple introduction of the filter. The clean filter will introduce a backpressure, which is increased by particulate loading. The clean filter base line backpressure is determined by the monolith design. The maximum value of particulate loading backpressure and the size of the filter will determine to some extent the frequency of regeneration. However, the amount of PM produced is influenced by uncontrollable factors such as driving mode, ambient temperature and humidity, thus exact regeneration frequency cannot be predicted accurately. The regeneration strategy determines whether a small fuel penalty will be sustained regularly or a large penalty less frequently. Most systems operate relatively infrequently since when sufficiently loaded and under the correct gas conditions, particulate combustion becomes self-sustaining allowing the external energy supply to be terminated. But this introduces the risk of thermal run away and filter damage. Lightly loaded filters do not produce sufficient exothermic energy for combustion to become self-sustaining.

Thermal regeneration systems are generally one of two configurations. In-line systems allow regeneration and filtering to take place simultaneously. By-pass systems divert exhaust gas whilst regeneration occurs. By-pass systems have proven more successful in practice due to lower energy requirement and simple thermal management of regeneration. The latter is due to consistent and controllable regeneration conditions independent of engine operating point. The design of in-line
systems is complicated by the need to operate over a wide range of exhaust temperatures and flows. However, the by-pass system also introduces complications, for example a means to divert and process the exhaust gas is required and large quantities of secondary air need to be supplied to support filter regeneration during by-pass. Some systems simply pass the gas through a conventional silencer, leading to untreated exhaust gas impacting overall emissions performance. Other designs use parallel filters, one filter is regenerated whilst another is filtering exhaust gas, solving the emissions issue but adding significant cost and packaging difficulties.

2.6.1 Oxi-Exothermic Regeneration Systems

Catalytic regeneration systems are often referred to as 'passive' regeneration systems. The previous sections of this thesis (Section 2.5.1 to 2.5.3) discussed systems that can be argued to be truly passive in that the catalysts do not provide a direct means to initiate oxidation. The catalysts merely reduce the PM ignition temperature from the normal 550 °C, and thus make regeneration initiated by high exhaust gas temperatures more likely. As previously discussed, fuel borne catalysts directly reduce the ignition temperature of PM. Catalysed filters use a precious metal washcoat to oxidise the soluble organic fraction (SOF) component of the PM. The heat energy released by this SOF oxidation, in addition to the exhaust gas temperature initiates the oxidation of the carbon component. Other systems, such as the CRT, use a catalyst to oxidise NO to NO₂, which acts as an oxidising agent for the PM at approximately 300 °C.

However, catalytic regeneration systems have been developed which do allow control of the point at which regeneration is initiated, and as such offer the control of 'active' regeneration systems (that will be discussed in the following sections of this chapter). The systems initiate regeneration by injecting hydrocarbons, from the engine fuel supply, into the exhaust gas, which are then oxidised by a catalyst (Gilot et al, 1993). The oxidation generates sufficient heat energy to regenerate the PM filter
downstream of the catalyst. There is a fuel consumption penalty as experienced with all 'active' or thermal regeneration systems. The fuel penalty experienced is influenced by the exact combination of the hydrocarbon fuel and the catalyst used, which determine the efficiency of oxidation and heat generation (Bandy and Graboski, 1993). These systems are often said to provide hydrocarbon enrichment of the exhaust gas and create situations similar to deNO\textsubscript{X} using hydrocarbons. Thus, some reductive effect on the exhaust gas NO\textsubscript{X} can be caused.

Injection can be performed at several points; into the face of the catalyst, into the exhaust manifold or into the engine cylinder. Ensuring an homogenous feed gas into the catalyst through atomisation, vaporisation and mixing of the hydrocarbons is essential for system efficiency (Heimrich, 1997). Packaging and cost of a fuel injector into the exhaust system can be avoided by making injections into the cylinder. Modern common rail and unit injector fuel injection equipment provide control for injection of fuel into the engine cylinders towards the end of the combustion event at approximately 90 °CA (crank angle) to 200 °CA after top dead centre (ATDC)(Peters et al, 1998). The timing of the injection is important to ensure the hydrocarbons are not partially oxidised towards the end of the combustion event (Klien et al, 1999). However, due to the low in-cylinder pressure during the late cycle injection the fuel spray can reach the cylinder walls and interfere with engine lubrication.

However, the increasing use of highly developed electronically controlled fuel injection equipment for enhanced diesel engine performance, emissions and NVH characteristics has meant that post injection of hydrocarbons is relatively simple. Thus the control to initiate regeneration and the simplicity of the regeneration system components (i.e. the existing fuel injection equipment and an oxidising catalyst) has meant that this active regeneration system has been adopted by a number of automotive manufacturers for further development, including Ford, PSA and Renault.
2.6.2 Initiation of Regeneration Using Engine Throttling Measures

Active regeneration systems input energy from an external source into the exhaust gas stream using a variety of methods such as fuel injectors or electrical heating systems. However, simply restricting the gas exchange processes of the diesel engine can lead to increased exhaust gas temperature to the extent where PM is ignited.

Early attempts to increase exhaust gas temperature used exhaust throttling to increase the in-cylinder residual levels, reducing the fresh air for combustion (Pattas, 1991). However, internal fouling of the cylinder walls and high thermal loads on the exhaust throttles caused reliability and durability issues such as poor cylinder sealing and exhaust throttle valve failures.

Diesel engines operating at part load have substantial amounts of excess air, which results in the relatively low exhaust temperatures. The lack of throttle control on the intake air minimises pumping losses and in part contributes to the relatively high fuel economy of the diesel engine. Reduction of the intake air flow at a given load (e.g. using a throttle) will reduce the air-fuel ratio towards the stoichiometric level resulting in increased exhaust gas temperatures which can be used for filter regeneration. However, throttling the intake air will create a depression in the intake system that will increase the fuel consumption of the engine through generation of pumping losses. However the short duration of the throttling process during regeneration will minimise any loss in fuel economy.

A number of considerations are required when specifying the position of the throttle within the intake system. Positioning of the throttle before the turbocharger compressor allows operation in the cold inlet air and can allow the air fuel ratio to be maintained at a predetermined level and thus maintain high exhaust gas temperatures (see Figure 2-5).
Figure 2-5 - Temperatures of the exhaust gas with and without throttling for constant air fuel ratio (Lambda = 2) (Adapted from Mayer et al, 2003)

However, whilst high exhaust gas temperatures are achieved the depression within the intake system has been suggested to cause oil-sealing problems within the turbocharger.

Throttling the air after the turbocharger compressor, even after the intercooler avoids the depression within the turbocharger system. The performance of the system in raising the exhaust gas temperature is believed to be the same as positioning the throttle prior to the turbocharger. The exhaust gas temperature after the turbocharger turbine was reported to increase by 300 K during part load engine operation without any detriment to engine response (Mayer et al, 2003). The air throttle could be used to control the oxygen flowrate through the filter using an air fuel ratio (lambda) sensor once regeneration has been initiated. Such a closed loop control system could minimise thermal gradients experienced by the filter.

Whilst throttling increases the exhaust gas temperatures to aid regeneration processes the system also leads to elevated NOx emissions and reportedly higher
noise emissions (Mayer et al., 2003) possibly from changes to the combustion heat release rate or acoustic interactions through the throttle system.

Throttling systems are capable of elevating the exhaust gas temperature to aid regeneration but not to the extent where such systems can be solely relied upon. Throttling systems are likely only to be used in combination with some form of catalyst to make the elevated temperatures achieved sufficient to cause PM oxidation.

2.6.3 Fuel Burner Systems

Fuel burners exploit the advantage of a large reservoir of fuel energy already available on the vehicle. The energy supply rate for electrical regeneration devices is much more limited. Fuel burners include control systems capable of maintaining the filter face temperature independent of engine operation. By-pass burner systems are of the general layout shown in Figure 2-6.
The burner shown in Figure 2-6 is supplied with fuel atomising air and combustion air. A common strategy to limit the thermal loading is to develop high burn rates at the beginning of regeneration, which then reduce towards its conclusion (MacDonald and Simon, 1988, Okazoe et al, 1996). This strategy tends to reduce peak temperatures. The fuel economy penalty during burner operation was reported to be less than that introduced by the unloaded filter. However, such systems are unsuitable for light duty applications due to the large demand for secondary air (~1000 l.min⁻¹ at STP) requiring large blowers that are difficult to package and introduce their own fuel penalty. The blower power and current requirements are also poorly matched to the 12 V electrical system of light vehicles. Smaller blowers have been used along with a portion of the exhaust gas to meet the gas flow requirement in an exhaust-fed by-pass system (Tuteja et al, 1992) shown in Figure 2-7 below. The secondary air and exhaust gas combine to provide the optimum flow conditions for efficient, thermally safe regeneration. The fuel economy penalty was not fully reported for assessment.
The most significant issue with the development of fuel burner systems is the design of the burner unit (see Figure 2-8). Ensuring reliable ignition is a major problem, preventing liquid fuel from entering the filter and its subsequent uncontrolled combustion causing damage (Wade et al, 1983). The burner should not create particulate emissions or allow liquid fuel to leak from the nozzle leading to hydrocarbon emissions. The most critical part of the burner design is the mixing liner. Poor design leads to unstable flames, significant pressure drops within the exhaust and non-uniform velocity profiles across the filter face leading to uneven loading and then local high temperature regions during regeneration. Another problem is a tunnel effect during regeneration where only the central core of the filter is regenerated. Tuteja et al (1992) used a bluff body diffuser at the filter entrance to alleviate this problem. Other difficulties reported include the burner extinguishing during heavy engine transients and the accumulation of PM on the fuel nozzle, preventing reliable ignition (Wade et al, 1983).
2.6.4 Electrical Heating Systems

Electrical-resistance (PR) heating regeneration systems consisting of heater coils positioned at the filter front face have been fitted to buses in service in major cities around the world (Turner et al, 1995). Catalytic filters have been used with these systems to reduce the particulate ignition temperature and thus minimise regeneration energy demands. Heat input ceases when the filter front face reaches a predetermined temperature, approximately 760°C at which point secondary air is supplied by a blower (Ha et al, 1991). Such systems generally have a high electrical demand, for example a truck system requires 160 A at 24 V equating to a power of 3.9 kW for several minutes (Ha et al, 1991). The power demanded from the engine is increased further due the inefficiency of the alternator. Electrical systems can require the engine idle speed to be increased to maintain battery charge, further increasing the fuel and emissions penalties from installing the system.
The requirement for a secondary air blower can be negated by the use of an exhaust gas feed (Kumagai et al, 1996). This hot gas reduces the electrical energy requirement to raise the filter temperature. Control over the bleed exhaust flowrate is required to prevent thermal runaway as the backpressure of the regenerating filter falls. Numerous problems were reported when designing a controllable bleed valve with adequate durability.

Deep bed filters, which filter PM throughout their structure, such as ceramic fibre or foam filters, can be constructed around heater elements. The heater elements are shaped and positioned to obtain uniform heating and regeneration. Trials on fork-lift vehicles have shown these systems to be more efficient than other electrical heating concepts due to the close coupling of the filter and the heater and they also proved highly durable due to the structural support the heater provides to the filter (Bloom, 1995).

A further derivation of a catalysed, electrical heating system uses a thermal storage device to heat secondary air that then passes through the filter, which is by-passed during regeneration. The secondary air was heated to around 950 °C, with a reported power requirement of 1.8 kW at 24 V DC for a small commercial vehicle (Romero et al, 1998).

2.6.5 Microwave Heating Systems

Electromagnetic microwave radiation causes certain material molecules to oscillate thereby heating the bulk material. The ability of a material to become heated is dependent on the dielectric properties. The power absorbed by a material is proportional to the imaginary part of the dielectric constant, the frequency of the incident radiation and the electric field. The imaginary part of the dielectric constant of diesel soot is much higher than that of Cordierite. Thus when soot in a Cordierite filter is exposed to microwaves it becomes heated directly, the Cordierite is only heated by conduction from the PM.
The ability to directly heat PM is a major advantage in terms of energy efficiency to achieve ignition temperature (Garner and Dent, 1989; Gautam et al, 1999). However, areas of low particulate loading within the filter can be cooled by conduction to the filter and convection to the exhaust gas, leading to such areas not achieving the required temperature and thus not regenerating. This has lead other researchers to use filter materials which do become heated by microwave radiation, such as silicon carbide fibre filters (Nixdorf et al, 2001). The microwave energy heats the filter material to a temperature whereby it ignites the filtered PM. This method tends to ensure more complete regeneration.

A number of systems have used a microwave supply to initially ignite the PM at the front face of the filter. The microwaves then cease and self-sustained regeneration is propagated to the rear of the filter. During the initial heating period the exhaust gas is often made to bypass the filter to reduce the heat energy lost to convection. However, this produces a significant untreated emissions penalty, some systems requiring bypass for as long as 15 minutes (Zhi et al, 2000a), or the added complexity of a parallel filter. Once the temperature has been increased sufficiently flow is redirected through the filter to supply oxygen for regeneration. The control of oxygen flowrate through the filter is crucial in the control of the self-sustaining regeneration process. A number of systems have reported thermal damage when initial particulate loading is relatively high, or incomplete regeneration when loading is low. Therefore, accurate monitoring of filter loading is required to ensure the correct amount of PM is present to support complete regeneration but which will not lead to thermal damage of the filter.

A method to assess PM loading using a microwave source has been reported by a number of researchers including Zhi et al (2000a). The concept used microwave attenuation through a Cordierite or ceramic foam filter to assess the PM loading as well as using the same source to initiate regeneration. A receiving antenna was positioned at the opposite end of the filter to the microwave source. Since the filter is transparent to microwaves, the attenuation of the signal is proportional to the
particulate loading. The attenuation constant of most materials varies with temperature. The constituents of the PM also change with temperature as water and the soluble organic fraction evaporate, further changing attenuation but in a predictable manner. These changes in microwave attenuation were evaluated to give a maximum error in filter loading measurement of around 10% (Zhi et al, 2000b). This method of assessing loading could be used to ensure regeneration is only performed once a predetermined critical mass of particulate had been collected which will support complete regeneration but not cause thermal damage to the filter.

The duration of the microwave heating period should also be carefully controlled to minimise energy input whilst ensuring regeneration is successful. Most microwave systems report input of 800 W to 1.2 kW using commercially available 2.45 GHz magnetrons. Other systems have reported significantly higher power requirements. The overall electric-microwave conversion efficiency of magnetrons is around 65% (Nixdorf, 2001), thus total energy demand is around 1.2 to 1.8 kW. The subsequent fuel economy impact is assessed via an averaging over the entire drive cycle. However, the substantial power usage during microwave operation may require electrical ancillary devices such as batteries and alternators to be increased in capability and size.

The most common problem reported in the development of microwave systems is ensuring even distribution of the microwave energy. Many systems report the regular occurrence of partial regenerations due to uneven microwave heating (Garner and Dent, 1989, Gautam et al, 1999), a problem that is exacerbated by uneven particulate loading. Various wave-guides, filter materials and system configurations have been tested and some found to improve the general performance (Garner and Dent, 1990).
2.6.6 Aerodynamic Regeneration Systems

The problem of thermally damaging the filter during PM oxidation can be eliminated if the particulates are removed from the filter by some other means prior to oxidation. Aerodynamic, compressed air or reversed pulse air regeneration systems remove PM from the filter by a number of short duration air pulses in the exhaust upstream direction. The short duration of the reversed flow prevents interference with engine operation. PM is deposited into a separate compartment where it is collected for oxidation or later disposal during servicing. There is no thermal or energy efficiency benefit in closely coupling the filter and engine. Thus the filter can operate in a thermally less demanding environment improving durability. These systems also offer the durability advantage of flushing the filter of accumulated ash and incombustible material. Such material increases the pressure drop across the filter or reduces the amount of particulate that can be accumulated; increasing the frequency of regeneration to the detriment of filter durability and engine fuel economy.

The aerodynamic dislodgement of PM is not simply the reverse process of filter loading. Since fluid flow follows the path of least resistance, larger pores are blocked first during filtration, followed by the next smallest until the smallest pores are blocked, the filter backpressure building continuously. Regenerative reverse flows dislodge the particulate from the largest pores first, through which much of the proceeding flow then occurs. The regenerating flow pressure behind the smaller pores is reduced, thus they are unlikely to become unblocked (Uchiyama et al, 1994). These continuously blocked pores provide a residual mass of PM that increases the post-regeneration backpressure across the filter. Residual pressure drop must be minimised to prevent detriment to engine fuel economy and increased regeneration frequency. The residual PM and thus the pressure drop is dependent upon the filter material microstructure, the regeneration characteristics (frequency, duration and reversed flow pressure), the engine operating point and the exhaust system layout.
The most influential factor in controlling regeneration effectiveness is the rate at which the reversed flow pressure rises (Ichikawa et al, 1995). High pressure-ramp rates yield the lowest values of residual particulate mass. The frequency and duration of the regeneration air pulses are much less influential. However, the sudden cooling effects of the reversed air flow can cause thermal shock damage to filters under test (Uchiyama et al, 1994). Later studies showed regeneration was far less effective at lower exhaust gas temperatures, possibly due to different types of PM associated with low exhaust gas temperature conditions or different modes of adhesion between the filter and particulates at low exhaust gas temperatures.

Aerodynamic regeneration systems require some method to deal with the high concentrations of PM entrained within the reversed air pulse. Some systems have dissipated the reversed flow momentum thus allowing the PM to settle into a collection chamber. However, this settling process is likely to take a significant amount of time as even the largest agglomerated particles can remain aerosol for a number of hours. The particulate is then removed during servicing or incinerated within the chamber. This incineration requires significantly less energy compared to oxidation within the filter as heating occurs away from the main exhaust flow reducing convective heat loss and the filter monolith does not have to be heated with the PM.

A common problem with these settlement systems is the re-entrainment of PM once forward exhaust flow is re-established. This is overcome by using through-flow systems. The reversed flow is allowed to exit to atmosphere through a second filter, however this filter then requires regeneration, possibly aerodynamically (Caceres and Levendis, 1995) (see Figure 2-9).
During standard operation the exhaust gases pass through the primary filter. During regeneration the filtered PM is flushed into the incinerator system, where it is either deposited on the electric incinerator or filtered in one of the secondary filters. These secondary filters are then regenerated aerodynamically until all PM has been incinerated. This is an extreme example, however, it indicates the major disadvantage that aerodynamic systems are generally very complex, costly and difficult to package within a vehicle application.

2.7 **Non-Thermal Plasma Regeneration Systems**

The application of non-thermal plasmas in the treatment of gases including the exhaust gases of internal combustion engines has been widely researched. Electrical discharge non-thermal plasma systems are able to initiate energy efficient chemical and thermal processes in the environment in which they exist. Particulate filter regeneration systems that utilise plasma have the significant advantage of not being directly dependent on the exhaust gas temperature that is determined by the drive
cycle. It is these abilities that make them attractive for the further research that is the subject of this thesis. However, many of the regeneration plasma systems that are discussed in published research to date are only capable of treating low gas flowrates and produce small oxidation rates, both factors making them currently impractical.

Plasmas, their characteristics and the specific application of plasmas to treat exhaust gases are discussed in greater detail in Chapter 3.

2.8 Particulate Filtration and Regeneration System Summary

A number of useful conclusions can be drawn from the preceding literature review.

Catalytic regeneration systems cause relatively little detriment to engine fuel economy. However, some catalysts require high exhaust gas temperatures to perform complete regeneration and can produce significant amounts of incombustible ash that needs to be removed from the filter to maintain adequate performance.

Thermal systems achieve PM oxidation at the natural ignition temperature of 550 °C by increasing the temperature of either the gas flow or the particulate itself through the introduction of energy from some external source. This energy requirement can impact the engine fuel economy (bsfc) and, thus needs to be minimised. Thermal systems do offer the advantage of performing regeneration independent of engine operation condition, thus can minimise the backpressure imposed by the loaded filter.

A problem associated with both catalyst and thermal systems is the potential to initiate uncontrolled self-sustained regenerations, especially under relatively high filter loadings. The exothermic heat released during these rapid regenerations can
cause thermal damage to the filter, especially to Cordierite wall flow filters that have relatively low thermal conductivity.

An ideal diesel particulate filter regeneration system should, therefore:

1. minimise filter loading to minimise the exhaust gas back pressure caused by the introduction of the filter system;
2. minimise energy consumption, thus minimise the impact on engine fuel consumption of introducing the filter system;
3. be capable of regenerating a filter at low filter loadings to prevent aggressive self-sustained regenerations, which cause high peak temperatures and large temperature gradients capable of damaging the filter structure;
4. be capable of regenerating the filter under all exhaust gas conditions likely to be experienced during the engine duty cycle;
5. be capable of regenerating a filter irrespective of engine fuel quality and its constituents;
6. not contribute to the build up of incombustible material and ash within the filter; and
7. require no servicing for the life of the engine.

No regeneration system discussed in published research to date has been able to fulfil all of these requirements satisfactorily. However, filter and regeneration systems will be required in the near future since diesel emissions legislations for passenger cars and heavy-duty applications are thought to have surpassed the levels attainable through in-cylinder controls alone.

Chapter 3 discusses the fundamental aspects of electrical discharges and plasmas; and then details the features of some of the published regeneration systems that use plasma to initiate rapid particulate oxidation.
The previous chapters have discussed the need for diesel particulate filters and the difficulties associated with different means of regeneration. All of the regeneration concepts discussed in Chapter 2 have advantages and disadvantages. The disadvantages for many of these systems have spurred the continued research into new regeneration concepts, including the application of plasma to regenerate filters. The novel Autoselective system that is the subject of this thesis aimed to use plasma generated by an electric discharge to regenerate diesel filters.

This chapter provides an overview of electrical discharges and the plasmas generated by them. The final sections provide a discussion of diesel filter regeneration systems reported in literature that use electrically generated plasma. These other systems all operate on the exhaust gas stream whereas the Autoselective system uniquely operates directly on the trapped PM.
3.1 Introduction to Plasma

A plasma is an approximately electrically neutral collection of positive and negative charges (Roth, 1995) in the presence of a background gas. Plasmas are subdivided into low temperature and high temperature groups. High temperature plasmas are fusion reactions that have particle energies above $10^7$ K. Low temperature plasmas are further divided into thermal and non-thermal groups. The ion and electron temperatures of thermal plasmas are very similar ($10^4$ K). However, the energy of the electrons ($10^5$ K) within the non-thermal plasma is significantly higher than that of the ions and background gas molecules (300 K) (Hippler et al., 2001). This distribution of energy gives the various plasmas different characteristics that enable them to be used in different applications, as will be discussed later.

The presence of charged particles cause the plasma to be influenced by external magnetic fields and electric fields, such as those generated between the electrodes in an electric circuit (see Figure 3-1).

![Figure 3-1 - Plasma generated between electrodes within an electric circuit](image)

The electric field within the electrode gap provides a kinetic energy to the charged particles within the plasma, causing them to move towards the electrode of opposing charge. This movement constitutes an electric current across the previously insulating electrode gap and is the basic process of an electric breakdown or electric discharge.
3.2 Electric Discharge in Gases – Formation of Plasma

Electrical discharge or breakdown is essentially the very rapid formation of a strongly ionised state under the action of an electric field. If the electric field is maintained for an extended period, a sustained discharge can be generated. The ionised region forms a highly conductive channel capable of carrying an electric current. The voltage required for this initial channel formation is generally referred to as the breakdown voltage.

3.2.1 Electric Discharge Mechanism

The electric discharge process is made up of a number of ionisation, collision and loss processes, all of which combine to determine if an electric discharge is initiated in the given conditions. A full mathematical description of these processes using classical gas laws and probability coefficients is provided in a number of texts including Kuffel et al (2000). However, Townsend first described the basic mechanism of an electric discharge in the early 20th century (as reviewed by Bazelyan and Raizer, 1998).

An electron can be emitted from the cathode of a dual electrode system, such as that shown in Figure 3-1, into the electric field. Electrons are regularly emitted from electrodes due to incident electromagnetic radiation providing sufficient energy to release the particle. Once in the electric field the electron is propelled towards the anode, gaining kinetic energy that provides it with the capability to make ionising collisions with background gas molecules. The primary electron loses some of its kinetic energy during an ionising collision and therefore two slow moving electrons are now present within the electric field. These electrons now gain kinetic energy from the electric field and can ionise molecules within the background gas. An electron avalanche develops, in which all electrons gain a drift velocity due to the electric field towards the anode, whilst the positive ions move towards the cathode. If the positive ions reaching the cathode have gained sufficient energy, they can
cause the emission of secondary electrons, which give rise to a new avalanche and sustain the discharge. Alongside this, electrons passing through the gas between the electrodes raise some of the molecules to an excited state. As the molecule returns to its non-excited state a photon is emitted. These photons either leave the electrode gap, making the discharge visible, or fall onto the cathode possibly causing the release of further electrons.

The point of electrical breakdown is where the discharge becomes self-sustaining. The number of electrons arriving at the anode is equal to the number of electrons generated within the gap, so that the total number of electrons remains the same. This is known as the Townsend criterion. The voltage at which this occurs for a given electrode configuration, background gas composition and state is the breakdown voltage.

A large number of factors influence the breakdown process and determine if a single avalanche occurs or a sustained discharge is created, including among others:

1. **Background gas density.** This determines the collision frequency and whether the free electrons can gain sufficient energy to cause ionisation between each collision. This is described by Paschen’s Law and is discussed later in this chapter.

2. **Electric field strength.** The applied voltage, the electrode separation and the shape of the electrodes determine the strength of the electric field applied to the plasma. If the electric field is too weak, the free electrons will not gain sufficient energy to cause ionisation within the background gas.

3. **Background gas composition.** Different gases require different energy to cause ionisation. In addition to this some gases are electro negative, meaning that they readily form negative ions through electron attachment and thus cause to the removal of free electrons from the discharge region.

4. **Electrode material.** Different electrode materials have different characteristics in terms of the energy required to liberate a free electron through ion impact or incident radiation at the cathode.
5. **Gas dynamic characteristics.** Bulk gas motion within the electrode gap in part determines the electron losses within the plasma. Gas flow through the discharge region can lead to increased electron diffusion losses (Raizer, 1991).

A sustained discharge is created when the number of electrons that lose energy before causing ionisation plus those lost through diffusion or attachment to gas molecules is lower than the number of secondary electrons released from the cathode. A range of different plasmas can be produced by a sustained discharge. The type of plasma produced is partly dependent upon the factors described above that have determined that a discharge will occur and also the electrical supply characteristics such as voltage and frequency.

### 3.3 Atmospheric Pressure Plasmas

Although early work on gaseous conduction was described by Coulomb in 1785, the scientific examination of electric discharges did not seriously start until the latter half of the 19th century and was closely related to advances in vacuum technology (Llewellyn-Jones, 1966). Vacuum tubes allowed relatively low voltage electrostatic supplies to produce sustained discharges that could be studied under laboratory conditions by researchers such as Faraday, Hertz and Thomson, leading to discoveries that opened up many areas of modern physics (Llewellyn-Jones, 1966). Electrical power supply development, including alternating current (AC) supplies, has subsequently allowed atmospheric pressure sustained discharges to be produced and studied.

Research into electric discharges initially centred on the production of discharges in partial vacuum pressures (i.e. below normal atmospheric pressure) where breakdown is more easily achieved. However, electrical discharges at atmospheric pressure are of great interest due to their growing importance in many applications today, some of which are discussed later in this chapter. At the atmospheric pressure the electrical strength of the gas insulation is highly influential on the discharge.
3.4 **Paschen’s Law**

Paschen’s Law states that the breakdown voltage of an electrode configuration is a function of the product of the gas pressure \( (P) \) and the electrode separation \( (d) \). However, more particularly it is the gas density that actually describes the number of gas molecules per unit volume. Hence it is the gas density that in part determines breakdown voltage; since it includes gas pressure and also temperature effects.

The general shape of the curve describing Paschen’s Law is shown in Figure 3-2. For a fixed electrode separation the collision frequency of electrons with gas molecules is low at low gas densities. Under these conditions there are insufficient gas molecules in the electrode gap to provide an electron avalanche and the positive ions required to initiate a discharge. The gas breakdown condition can only be met by increasing the probability of ionising collisions. At higher gas densities the collision frequency increases due to the larger number of gas molecules. However, the increased collision frequency prevents an electron gaining sufficient kinetic energy between collisions and this reduces the probability of ionisation. The applied voltage must, therefore, be increased to produce ionising collisions under high gas density conditions. Thus there is an intermediate density at which there is a minimum breakdown voltage for a given electrode configuration and gas combination (see Figure 3-2).

![Figure 3-2 - Paschen's curve. Breakdown voltage as a function of the product of gas density and electrode separation \((\rho \times d)\)
3.5 *Gas Composition Affects on Breakdown Characteristics*

Practical gas mixtures contain impurities from environmental and man-made sources; all of which can affect the breakdown and discharge characteristics. For example, impurities such as argon can reduce the breakdown voltage of a gas mixture since it is relatively easily ionised and thus provides electrons to create an avalanche at the beginning of the breakdown process. Other impurities such as water vapour, as found in the exhaust gases of internal combustion engines, can increase the electrical breakdown voltage of a gas mixture by removing electrons from the ionisation process. Such electro-negative gases form negative ions by attaching themselves to free electrons in a gas, thereby preventing these electrons from being active within the plasma. The exact effects of increased water vapour (or humidity) on breakdown processes have not yet been precisely quantified since they are heavily influenced by electrode configurations and the exact composition of the gas in which breakdown occurs (Allen *et al.*, 1991). Thus, the effect of increased humidity on electrical breakdown using a particular system in a particular environment requires specific investigation.

3.6 *AC Discharges*

Direct current (DC) and alternating current (AC) (1 kHz to 10 GHz) power supplies are both capable of producing electrical discharge plasma. However, power supplies that alternate at frequencies above 1 kHz have a number of advantages over DC supplies including their ability to cause electrical breakdown at voltages below DC values under similar gas conditions (Beynon, 1972).
At relatively low alternating frequencies (i.e. ≤100 Hz), breakdown must occur at the beginning of each half cycle of current as the plasma is dispersed before the next cycle is initiated. If all the electrons and positive ions reach the anode and cathode respectively before the voltage builds back to its maximum value in the opposite direction, then the discharge will be extinguished.

However, whether breakdown occurs or not in AC circuits depends to some extent on the value of the voltage immediately after the current falls to zero. The voltage at the zero current part of the cycle depends on the parts of the circuit external to the discharge. In a circuit containing resistance only, the current and voltage are completely in phase. The likelihood of breakdown occurring is small because when there are few ions reaching the cathode (current, \( I \approx 0 \)) those that do arrive at the electrode have relatively little energy and are unlikely to cause electron release. However, a circuit containing inductive or capacitive elements has a phase difference between the voltage and current. Thus during the part of the cycle when there are relatively few ions striking the cathode (i.e. \( I \approx 0 \)), those that do reach the electrode are more likely to have sufficient energy, from the non-zero voltage, to release an electron and sustain the discharge. Therefore, AC circuits in which sustained electrical discharges are sought generally have capacitive reactance rather than being purely resistive (Roth, 1995) as this reduces the voltage required to initiate electrical breakdown.

The Townsend breakdown criterion explains that the rate of generation of electrons is balanced by the rate of loss of electrons from the discharge region to the electrodes, diffusion and negative ion formation. This balance condition applies to high frequency breakdown. As the frequency rises, the charged particles moving within the plasma have their direction of motion reversed before they can reach the electrodes. Therefore, the charged particles remain in the plasma for longer periods and make more ionising collisions. With DC and low frequency electrical supplies, the secondary electron emission at the cathode is the main process for producing secondary electrons and thus sustaining the discharge. However, if the frequency is increased, the cathode emission rate reduces because the positive ions are unable to...
reach the electrode during one half cycle of the electric field. Initially the breakdown voltage rises as the frequency increases from DC, but then falls again as frequency increases further as ionising collisions in the gas take over in generating secondary electrons (see Figure 3-3). However, as frequency is further increased, the electrons within the plasma simply oscillate about a mean position with an amplitude that is much smaller than the electrode separation and none of the electrons reach the anode. The positive ions have an even smaller amplitude since their velocity is 100-200 times lower than that of electrons (Kuffel et al, 2000). The electrons tend to diffuse out of the gap as any collisions in which they are involved generally result in a change of their direction. The discharge balance condition for these AC conditions shifts to one where the rate of electron generation by ionising collisions must be greater than the diffusion of electrons out of the electrode gap. The frequencies at which the breakdown voltage reaches its first maximum value, then falls to a minimum and then rises again as diffusion effects become important are heavily dependent upon the specific gas conditions, electrode separation and configuration used (Beynon, 1972).

![Breakdown Voltage vs Frequency](image)

**Figure 3-3 - Illustration of breakdown voltage against frequency for a given electrode configuration under given gas conditions.**

Within the region where the breakdown voltage is a minimum, the plasma loses few energetic particles to the electrodes and each electron within the plasma experiences a maximum number of ionising collisions. The large number of ionised particles and electrons within the plasma make these AC discharges particularly productive in
modifying the background gas chemistry or generating free radicals through dissociation and ionisation processes (Roth, 1995). As will be seen later, these properties are attractive for soot oxidation.

3.7 Discharge Voltage and Current Characteristics

A range of plasmas with various voltage and current characteristics (see Figure 3-4) can be generated using a simple electrode and power supply arrangement (see Figure 3-5). As the voltage is increased from zero, the current rises initially and then remains nearly constant. This constant current is made up of electrons emitted from the cathode surface due to incident radiation, and as such, is dependent upon factors including the cathode area and material and the gas density. These electrons do not gain sufficient energy to cause ionisation within the gas between the electrodes but travel to the anode by the applied electric field. This region is known as the pre-breakdown region.

As the voltage is increased, the current increases at an exponential rate. This rising current is due to the increasing energy gained by the electrons emitted from the cathode, enabling them to cause ionisation within the gas and thus increase the current flowing between the electrodes. This is the point of electrical breakdown, and defines the breakdown voltage. This section of the voltage-current characteristic is referred to as the corona or sometimes Townsend discharge region (see Figure 3-4).

Post breakdown the electrical characteristics of the circuit and power supply play an important role in controlling the discharge current. If the circuit has a low resistance the discharge current will rise rapidly through the glow discharge region and into the arc discharge region (see Figure 3-4).
Chapter 3 - Electric Discharge Plasma - Introduction and Applications

3.8 Discharge Types and Applications

The range of voltage and current characteristics shown in Figure 3-4 provide the different plasmas with different capabilities that are used in various applications, including exhaust gas aftertreatment. The following sections discuss the generic characteristics of the different types of plasma and how they are suited to different applications.
3.8.1 Corona Discharge (Townsend Discharge)

Non-uniformities within the electric field occur with many electrode configurations where the electrode gap is not constant or the electrode geometry is such as to increase the electric field in certain regions. The number of electrons generated within the gas by the primary ionisation process is different throughout the electrode gap and this leads to filamentary partial discharges namely a 'corona discharge'.

Corona discharges receive their name from their similarity to the corona surrounding the sun. They generally occur around HV conductors of small radius, can emit a crackling noise and can cause significant power loss in transmission lines. Corona discharges can occur in a number of forms but generally appear in a streamer or filamentary mode characterised by short duration (e.g. 10 - 100 ns) current pulses with relatively high current values. In this form corona discharges occur briefly and extinguish without the subsequent formation of glow or arc discharges, and as such they can be referred to as partial discharges. The non-continuous, short duration of discharge operation means that the time averaged discharge current is low (see Figure 3-4).

3.8.2 Glow Discharge

The glow discharge regime is achieved when the current is allowed to increase sufficiently (>10^-5 A), as shown previously in Figure 3-4 and the discharge becomes clearly visible. Through the glow discharge region the current can increase by four orders of magnitude (i.e. 10^-5 to 10^-1 A).

The glow discharge is a uniform continuous discharge and, therefore, is not the sum of a large number of filamentary elements. Acoustic and high-speed camera investigations have confirmed the continuous nature of the glow discharge (Trunec et al, 1998). At atmospheric pressure a glow discharge requires an alternating source.
of frequency greater than 1 kHz (Kanazawa et al, 1990). Below this frequency the discharge becomes the sum of individual discharges that occur at each cycle of the alternating voltage. The continuous nature of AC glow discharges has been found to be beneficial in a number of applications such as industrial gas treatment and generation.

As the current increases, the glow discharge expands to cover the whole cathode surface area at which point the current does not rise further. The discharge has no other means of efficiently generating electrons without increasing the voltage and the discharge enters the abnormal glow region. The voltage between the electrodes rises until it reaches a maximum and then begins to fall, as other methods to increase the current now become effective in the arc regime. In this region, electron generation processes, such as thermionic and field emissions, that do not operate during the glow discharge play an important role.

3.8.3 Arc Discharge

Humphrey Davy first discovered the arc discharge in 1810. He connected two carbon electrodes to a battery and found that a large current passed through them when the tips were brought together. On separating the electrodes the current continued to flow, an exceptionally bright discharge occurred and the cathode became white hot. The arc is so called because the air around the discharge is heated to the extent where convection currents force the discharge to assume the shape of an arc.

The arc discharge is characterised by high current flow and the release of large amounts of heat energy through Ohmic heating effects. This heating can eventually lead to the generation of thermal plasmas where the ion and gas temperatures are similar to those of the electrons. Arc discharges are generally used where very high levels of localised heating are required such as in metal cutting and welding applications.
3.8.4 Dielectric Barrier Discharge (DBD)

Modifying the electrode set-up used to produce an AC glow discharge at atmospheric pressure by applying a dielectric barrier to one or both of the electrodes (see Figure 3-6) leads to the production of a Dielectric Barrier Discharge (DBD). The dielectric barrier acts in a similar manner to a capacitive element allowing brief periods of current flow before stopping the discharge at a particular location and effectively recharging.

![Figure 3-6 - Common planar DBD configurations. (Adapted from Hipler et al, 2001)](image)

A DBD consists of a large number of simultaneous discharges at different locations across the dielectric barrier. These micro discharges or filamentary elements only have a duration of a few nanoseconds. The distribution of these small discharges over the whole electrode area creates a discharge of a relatively large volume of plasma compared to the narrow channels of the glow, corona and arc discharges. The nature of the plasma makes it especially suited to applications where large volumes of gaseous species are required such as industrial ozone production for the treatment of drinking water (see Figure 3-7). The radiation and light emitted by
DBDs is used in high power CO₂ lasers for welding and cutting metals and also in flat display screens where the large, distributed surface area of the discharge provides UV radiation that is converted by phosphor coatings into the red, green and blue colours for display.

![Image](image.png)

**Figure 3-7 - Industrial Dielectric Barrier Discharge ozone generator for water treatment (Hipler et al, 2001)**

### 3.9 *Plasma Based Diesel Engine Exhaust Particulate Abatement Systems*

The use of non-thermal plasma technologies for the treatment of engine exhaust gases including particulate filter regeneration is a growing area of research, but no technology has thus far been developed sufficiently for practical production application. All the plasma systems discussed in published research operate on the gas phase of the exhaust stream. They enhance the oxidising nature of the exhaust gases in a similar manner, but not identical, to some catalytic based regeneration systems that use NO₂ to oxidise the PM as discussed in Chapter 2. However, plasma systems offer the distinct advantage over catalytic systems, such as the CRT, in that they can operate under any practical exhaust temperature conditions. Catalytic regeneration systems on the other hand do reduce the ignition temperature of the PM but still require a gas temperature of 250-300 °C to make their catalysts operate, making continuous regeneration virtually impossible to guarantee under all engine operating conditions. The exhaust gas constituents in part determine the exact
Chapter 3 - Electric Discharge Plasma - Introduction and Applications

chemical reactions that occur within the plasma. Oxygen is readily dissociated compared to nitrogen. The energy input by the plasma simply kinetically and electrically excites nitrogen molecules, rather than causing chemical changes (McAdams, 2001). Oxygen dissociation means that oxygen containing non-thermal plasmas will be oxidative in nature, characterising the processes used by many plasma based filter regeneration systems. Penetrante et al (1997) suggested chemical changes of nitrogen (N₂) molecules are unlikely in plasma, and such reactions in high concentration nitrogen environments are energetically inefficient. Exhaust gases will include other constituents such as carbon dioxide and water vapour. However, the likelihood of water vapour and carbon dioxide dissociation in non-thermal plasmas is also low (McAdams, 2001), thus these gases will not tend to contribute to the production of reactive, oxidising species.

Most filter regeneration systems that use plasma attempt to alter the chemical nature of certain components within the exhaust gas, generating reactive radicals and NO₂, which then oxidise the carbonaceous PM (Okubo et al, 2004). The exact nature of the oxidation process appears to be not well understood since it is rarely discussed in detail or clarity in the published literature. Research is continuing to establish the steps within the mechanism involved in filter regeneration by these reactive species. General agreement seems to be that the NO within the exhaust gases is oxidised to NO₂ by the plasma, similar to the action of the platinum catalyst of the CRT system. The NO₂ then reacts with the carbon to form carbon dioxide, carbon monoxide and nitrogen monoxide. One system (Matsui et al, 2003) used plasma generated by a pulsed voltage of 20 kV at 120 kHz to produce reactive chemical species. The system was said to require relatively high oxygen levels compared to those experienced within an engine exhaust under high load conditions, but specific data was not given. The system was also reported to produce sufficient amounts of CO to require subsequent use of a platinum catalyst.

NO has also been oxidised to NO₂ using a pulsed dielectric barrier discharge (DBD) (Yamamoto et al, 2003). The system was developed to provide a more efficient conversion of exhaust NO to NO₂ than could be provided by the platinum catalyst of
the CRT system. Platinum catalysts offer a conversion efficiency of approximately 50%, where as an 80% conversion was achieved with plasma generated by a 45 kV, 2-3 Amp, 420 kHz supply (Yamamoto et al, 2003). The power required by the supply to produce this discharge was not stated, thus the actual load on the engine and fuel economy cannot be assessed. The high operating voltage means the electrical insulation of the system was critical. The NO to NO₂ conversion tests were conducted in gas flowrates of only 1.5 L.m⁻¹ @ STP, which is unrepresentative of almost all diesel engines. Yamamoto et al (2003) then stated that the conversion efficiency of the plasma fell from its 80% peak as the gas flowrate increased. Regeneration tests using the system showed 75% of trapped PM was oxidised, however, the critical data was that only 135 mg of PM was oxidised from the diesel filter in nearly seven hours of operation at the low gas flowrates (a 4 litre, turbo charged diesel engine can produce PM at 5-6 g.hr⁻¹). Other plasma systems that operate in a similar manner also require very low flow rates and others have reported some dependency on gas composition, such as a minimum oxygen requirement of 10% (Matsui et al, 2001) which limits the system potential application.

Other plasma systems work more generally on the exhaust gas composition to generate radicals, such as ozone and nitric oxides. A system developed by Atmospheric Glow Technologies (Kelly et al, 2003) used a porous metallic filter as one electrode in a dielectric barrier system. A discharge was then generated in the electrode gap by a 10 kV, 5 kHz power supply as shown schematically in Figure 3-8.
Chapter 3 - Electric Discharge Plasma – Introduction and Applications

The discharge power was 200 W during operation, averaging to an energy consumption of 15 J.l⁻¹ of exhaust gas. The total power required or power supply efficiency was again not reported thus the impact of the regeneration system on engine fuel economy could not be evaluated. This system suffered from significant flowrate restrictions. A 4.5 kW rated engine, operating at 3600 rpm, with an exhaust flowrate of 0.77 kg.min⁻¹ was reported to require two or three, 10-inch long filters. This was due to the small gap in which the plasma operated, through which exhaust gas must pass to be treated. The size of this gap strongly influenced the density of the plasma, which was then directly related to the rate of PM oxidation. However, reducing the gap size would increase the backpressure imposed by the system on the engine. The gas flowrate and backpressure determine the number and size of the metallic filters required to treat the exhaust gas.

A system developed by AEA Technologies (McAdams, 2001) was reported to use non-thermal plasma to produce active chemical radicals similar to the Atmospheric Glow Technologies system described above. However, this system used filamentary or micro discharges of 1-10 ns duration, in a packed bed filter that acts as the dielectric barrier for the discharge, The number of particles, as a function of size, was monitored at the inlet and outlet of the AEA system. All particle sizes were reduced
by a similar percentage, demonstrating good filtration capabilities of the system and also showing the plasma was not merely breaking down larger particles into ultrafine particles that then passed out of the exhaust without being oxidised. The upper limit of particulate oxidation efficiency was approximately 0.34 (kW.h).g⁻¹ or alternatively expressed, 2.94 g.(kW.hr)⁻¹ (McAdams, 2001).

Electrical discharge, non-thermal plasma systems are capable of initiating chemical and thermal processes that mean they can be used to initiate particulate filter regeneration. The controllable nature of the plasma systems means that aggressive, potentially filter damaging regeneration reactions are unlikely to be initiated, similar to the advantage offered by passive catalytic systems. Alongside this the independence from exhaust gas temperature means the plasma systems offer similar control to that of a thermal regeneration system. However, all the filter regeneration plasma systems that are discussed in published research to date are only capable of treating low gas flowrates and produce limited oxidation rates, both factors making them currently impractical for application.

The following chapters detail the research conducted to investigate the performance characteristics of a novel ‘Autoselective’ electric discharge concept for directly oxidising PM and the initial stages of development towards a practical system. The work established the potential of the Autoselective System to regenerate a standard, Cordierite wall flow filter in the exhaust of a commercial, heavy-duty diesel engine whilst consuming minimal power. As will be explained later, this system is fundamentally different to other plasma systems and has a unique set of characteristics that make it particularly attractive for diesel particulate filter regeneration.
4 Experimental Apparatus and Techniques

A diesel particulate filter regeneration system should be capable of operating under normal diesel engine exhaust conditions. The preliminary feasibility work conducted on the Autoselective plasma regeneration system that is the subject of this research was conducted in quiescent air, at ambient temperature and pressure. These conditions are significantly different from the high temperature gas flow with reduced oxygen concentration and increased water vapour concentration of the diesel engine exhaust.

A real engine exhaust system would provide little independent control of the individual gas characteristics such as temperature, flow rate and oxygen content. Identification of the key variables and their effects would therefore be difficult to achieve. An environment was required in which the major exhaust variables could be controlled independently and filter regeneration could be easily monitored and observed.
4.1 Hot Flow Rig

A rig was developed with an electrical blower and heater to provide a stream of heated air, whose composition could be controllably changed through the introduction of gaseous components including carbon dioxide and water vapour, thus simulating the exhaust gases from a diesel engine. Other researchers (Rumminger et al., 2001) have used propane burners to provide the combustion products and heated gas flow for filter regeneration system investigation. Whilst burners supply some of the trace combustion products and to some level a reduced oxygen concentration within the gas flow, the combustion process does not provide complete independent control of all variables.

4.1.1 Hot Flow Rig Requirements

The typical flow conditions likely to be experienced within the exhaust system of an off-highway diesel engine of a suitable size to be fitted with a 5.66 inch diameter, 6 inch long, 100 cpsi wall flow filter are summarised in Table 4-1:

<table>
<thead>
<tr>
<th>Gas Characteristic</th>
<th>Typical Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (Post turbocharger)</td>
<td>100 – 700 °C</td>
</tr>
<tr>
<td>Flowrate (l.min⁻¹ at STP [see note])</td>
<td>Upto 4000 l.min⁻¹</td>
</tr>
<tr>
<td>Front filter face axial gas velocity (corrected to STP)</td>
<td>Upto 4 m.s⁻¹</td>
</tr>
<tr>
<td>Axial velocity within filter channel (corrected to STP)</td>
<td>Upto 8.5 m.s⁻¹</td>
</tr>
<tr>
<td>Filtration velocity through channel wall (corrected to STP)</td>
<td>Upto 3.5 cm.s⁻¹</td>
</tr>
<tr>
<td>Water vapour concentration above ambient</td>
<td>0 – 10 % (Bauer, 1996)</td>
</tr>
<tr>
<td>Oxygen concentration</td>
<td>2 – 21 % (Bauer, 1996)</td>
</tr>
</tbody>
</table>

Note: Volumetric flow rates and velocities corrected to 0 °C, 101 kPa (STP)

Table 4-1- Typical diesel engine exhaust conditions that were required to be simulated within the hot flow rig and in which the Autoselective regeneration system was to be tested

The hot flow rig was designed to simulate the above conditions, allowing regeneration effectiveness to be assessed under all conditions likely to be experienced within the engine exhaust.
The exhaust gases from a diesel engine contain a number of species in relatively small concentrations such as carbon monoxide, oxides of nitrogen (NOx), polycyclic aromatic hydrocarbons (PAH), aldehydes and other combustion-generated radicals. Electric discharge power and discharge regimes tend to be affected only by relatively large concentration (5-10% by volume) components within the background gas (Meek and Craggs, 1978). In the case of diesel exhaust gases, the main constituents are nitrogen, carbon dioxide, oxygen and water vapour. Thus the test gas was considered as essentially air (nitrogen and oxygen) with increased carbon dioxide (CO\textsubscript{2}), increased water vapour and reduced oxygen concentrations. Many of the trace components within the engine exhaust gas are difficult to generate without some form of combustion process. However, combustion processes are very dependent upon the conditions in which they occur and thus would introduce instabilities and uncontrolled factors that the hot flow rig was intended to eliminate.

4.1.2 Hot Flow Rig Components and Design

The hot flow rig was designed to simulate the conditions outlined in Table 4-1 and consisted of four main components (Figure 4-1):

1. high flowrate blower to provide a gas flow velocity of 8 ms\textsuperscript{-1} at the loaded wall flow filter front face in a profile similar to that expected at a filter within a real engine exhaust;
2. heater unit to controllably raise the temperature of the gas flow to a maximum of 700 °C;
3. an optical section to allow observation and recording of the electrical discharge appearance and movement under various flow conditions; and
4. a filter holder that allows easy access to the filter monoliths for assessment of regeneration effectiveness and efficiency.
Chapter 4 - Research and Experimental Techniques

Electrical heater and blower unit to provide simulated exhaust gas

Observation chamber and electrode access

5.66" diameter, 6" long wall flow filter canister

(a)

Figure 4-1 - Hot flow rig (HFR) (a) schematic of HFR, (b) HFR with ancillary equipment.

(b)

4.2 Monitoring and Controlling Flow Rig Conditions

The hot flow rig (HFR) provided the ability to independently control the variables of the simulated exhaust gas stream to assess effects on discharge behaviour and regeneration performance. The following sections discuss the methods and
equipment used to monitor and control the characteristics of the simulated exhaust gas.

### 4.2.1 Gas Flow Rate

The total gas flowrate through the rig was measured using an orifice plate and digital manometer. The orifice plate created a restriction through which the gas must flow. The sharp restriction caused a vena contracta in proportion to the size of the orifice restriction compared to the standard pipe diameter in which the plate is situated. Measurement of the static pressure upstream of the orifice plate and where the vena contracta existed downstream allowed the gas flowrate to be calculated from a derived form of Bernoulli’s equation as follows:

$$Q = C_d \sqrt{\frac{2\Delta p}{\rho}} \frac{A_2}{\sqrt{1 - \left(\frac{A_2}{A_1}\right)^2}}$$  \hspace{1cm} \text{Equation 4-1}$$

where $Q$ is the volumetric flowrate ($\text{m}^3\text{s}^{-1}$), $A_1$ is the pipe area ($\text{m}^2$), $A_2$ is the area of the orifice ($\text{m}^2$), $\rho$ is the gas density ($\text{kgm}^{-3}$), $\Delta p$ is the differential pressure (Pa) and $C_d$ is the discharge coefficient of the given orifice plate installation. The discharge coefficient of the orifice plate installation is determined through a calibration flow measurement. The discharge coefficient for the orifice plate installation used in the HFR was 0.64 (supplied calibration certificate for given installation geometry, Air Products, 2002).

An orifice plate and its pressure tappings must be correctly installed to ensure the flow profile entering the orifice is uniform, thus ensuring the vena contracta is uniform and the pressure measurements are in the correct positions for the flow profile. The orifice plate within the hot flow rig and its installation conformed to British Standard BS 1042 and ISO 5167. The calibrated digital manometer had a resolution of $+/− 1\text{ Pa}$, providing a minimum accuracy of $0.5\text{ l.min}^{-1}$ at $0^\circ\text{C}$. The
temperature of the gas passing through the orifice plate was measured 60 mm upstream using a K type thermocouple, allowing determination of the gas density for the orifice plate flow rate calculation (Equation 4-1).

### 4.2.2 Flow Rate Control

The gas flowrate through the HFR was controlled using a ball valve situated upstream of the orifice plate. The valve was positioned a distance the equivalent of 30 pipe internal diameters upstream of the orifice plate, allowing the gas flow profile to return to the fully developed state after passing through the ball valve. This ensured the flow profile through the orifice plate was symmetrical and thus pressure differential measurements were accurate.

### 4.2.3 Filter Front Face Velocity Profile

A Kiel probe was used to determine the axial gas velocity profiles through the vertical and horizontal centrelines of the filter face to locate a region of relatively constant gas flow in which the discharge could be tested.

A Kiel probe was used to measure the stagnation pressure of the gas flow at locations across the filter front face. Measurement of the gas static pressure within the HFR allowed calculation of the gas velocity at the Kiel probe location using a form of Beroullli’s equation:

\[
V = \sqrt{\frac{2(p_0 - p)}{\rho}} \quad \text{Equation 4-2}
\]

where \(V\) is the gas velocity (m.s\(^{-1}\)), \(p_0\) is the stagnation pressure at the Kiel probe (Pa), \(p\) is the static pressure within the same region (Pa) and \(\rho\) is the density of the gas (kg.m\(^{-3}\)). A K type thermocouple was located at the filter front face. The
temperature and static pressure data is used to determine gas density for Equation 4-2.

A central core region within the gas flow with a diameter of 110 mm was found to have a velocity that varied by only 0.3 m.s\(^{-1}\) at a peak velocity of 10 m.s\(^{-1}\) at 0 °C. Thus all tests conducted within this central region were known to have experienced a constant velocity flow field.

### 4.2.4 Gas Temperature

The gas temperature through the filter was measured using two K type thermocouples, one positioned approximately 10 mm from the front face of the filter to measure inlet gas temperature and one positioned 10 mm from the rear of the filter to measure the outlet gas temperature. The gas temperatures in the experimental Chapters of this thesis refer to the gas temperature measured by the thermocouple at the front face of the filter.

Regeneration tests were only conducted once the inlet and outlet gas temperatures had both stabilised for 3-4 minutes. This ensured that the filter monolith temperature had stabilised thus minimising any effects that could be caused by temperature gradients within the filter or significant differences in gas and filter monolith temperature.

The thermocouples were connected to a calibrated digital readout, providing the temperature in degrees Celsius. The thermocouples were positioned at least 40 mm from the HV electrode when the discharge voltage was under 25 kV. If the thermocouple was positioned in close proximity to the HV electrode, discharge to the metallic thermocouple sheath was likely and would cause significant electrical interference rendering temperature measurement impossible. If the discharge voltage was increased then the HV electrode and thermocouple separation must also be increased.
4.2.5 Oxygen Concentration

The oxygen concentration of the simulated exhaust flow was reduced from ambient levels using a dilution gas of carbon dioxide (CO\textsubscript{2}) and nitrogen (N\textsubscript{2}) introduced before the heater unit. The CO\textsubscript{2} simulated the presence of combustion downstream of the filter, as would occur in an engine, and then volumetric proportion of N\textsubscript{2} was replenished to approximately 79%. This resulted in an overall reduction in oxygen concentration, an increase in carbon dioxide concentration whilst maintaining nitrogen levels.

The volumetric flowrate of the dilution gas was measured using rotameter flowmeters specifically calibrated to the particular gas used. The total gas volume flowrate through the rig was measured downstream of the dilution gas insertion point using the orifice plate described previously. The oxygen volume concentration was calculated from these flowrate measurements using:

$$O_2\% = \frac{0.21 \times (\text{Flowrate}_{\text{Total}} - \text{Flowrate}_{\text{Dilution gas}})}{\text{Flowrate}_{\text{Total}}} \times 100\% \text{ Equation 4-3}$$

The accuracy of the O\textsubscript{2} concentration calculation was assessed using a Pfeiffer Thermostar mass spectrometer. The operating principles of mass spectrometers are discussed in greater detail in Chapter 6 of this thesis. However, briefly here, they are a means to accurately identify and measure the relative concentrations of the constituents of gases or vapours. The mass spectrometer confirmed the O\textsubscript{2} calculation was accurate to within ±0.7 % volume concentration. The discrepancy is believed to be due to the limited accuracy with which readings can be taken from the gas rotameters.
4.2.6 Water Vapour Concentration

The water vapour concentration of the air flow was increased by introducing liquid water, preheated to 95 - 100 °C, into the heater outlet. The hot gases from the heater vaporised the water and entrained this vapour into the gas flowing through the rig. The water is heated prior to insertion into the hot flow rig to ensure rapid vaporisation and entrainment without significantly cooling the gas stream. The rig was heated to the required test temperature prior to water insertion. This prevented water vapour from condensing and entering the filter under test or falling out of suspension thus creating non-homogenous gas conditions within the rig. The gas temperature measured at the rear of the filter was maintained above 150 °C under increased humidity conditions. This ensured that there was no condensation of water vapour within the rig or filter.

The hot water was introduced into the airflow using a burette that allows measurement of the volume flowrate. The specific volume of the saturated water at the ambient pressure was determined from saturated liquid tables (Cengel and Boles, 1998) and allows the mass flowrate of water to be calculated. The pre-heated water was vaporised rapidly by the heated gas stream without significantly cooling the air. Measurement of temperature and static pressure at the filter front face allows determination of the superheated steam specific volume from superheated gas tables (Cengel and Boles, 1998). The percentage volume of water vapour could then be calculated. The accuracy of the calculation method was tested against the water vapour concentration measured using a Pfeiffer Thermostar mass spectrometer, and was found to agree to within ±0.8 % of volumetric concentration.

4.3 HFR Capabilities

The stabilised capabilities of the assembled rig were measured and are shown in Table 4-2.
Table 4-2 - Hot flow rig capabilities and characteristics

Comparing Table 4-2 with Table 4-1, the HFR was capable of simulating the wide range of the major gas characteristics of an off highway diesel engine exhaust. The rig provided a controlled environment in which the regeneration system can be tested under the various states of the major gas variables that are likely to be experienced within an engine exhaust system.

### 4.3.1 Rig Limitations

The HFR had differences in the flow patterns around the front face of the filter compared to those of a real engine. For example, the HFR could not simulate the pulsed nature of the exhaust flow from a reciprocating internal combustion engine. The pulsing in the flow of a real engine would lead to increased turbulence around the front face of the filter. However, the turbine for the turbocharger will reduce the magnitude of these pulses. The shape of the rig observation chamber in front of the filter is also different when compared to the inlet cone of a diesel filter canister. The geometric differences are likely to alter the details of the flow field established around the front face of the filter compared to that on a real engine.

Early tests indicated the gas flowrate is an important factor in determining the discharge behaviour and regeneration rate achieved. The higher turbulence associated with high flow rates is believed to be the controlling factor (discussed further in Chapter 5). Thus these differences in flow patterns between the hot flow rig and on-engine exhaust filter systems were likely to produce some differences in the regeneration behaviours achieved in the two different conditions. Therefore, on-
engine testing would be required to validate the results achieved during HFR investigations.

4.4 Electrical Discharge System Power Supply and Instrumentation

4.4.1 High Frequency, High Voltage Power Supply

The variable high frequency, high voltage electrical power supply used to produce an electrical discharge within the HFR for development testing was significantly different in size and range of operation to the power supply that is expected to be used by any production intent device. The schematic layout of the experimental power supply setup is shown in Figure 4-2.

![Diagram of Experimental Power Supply](image)

**Figure 4-2** – Diagrammatic representation of the experimental electrical power supply used for Autoselective discharge investigation within the hot flow rig

The first signal generator provides a square wave, which triggers the second signal generator to produce the discharge voltage sinusoidal waveform. The square wave was used to modulate the overall energy input from the discharge by switching the power supply on and off for known periods of time or duty cycle (discussed further...
in Chapter 6). The frequency and symmetry of the square wave could be altered to change the on or off time period independent of the other. The second signal generator provided a sinusoidal wave output, at the discharge voltage frequency. The energy of this sinusoid was increased using an Amplifier Research 700A1 10 kHz - 1 MHz power amplifier; the voltage increasing to 200 – 350 V. This voltage was then stepped up to the discharge voltage (8 - 12 kV pk) using a high frequency transformer. The transformer operating frequency had to be matched to the specific discharge frequency under test to ensure adequate secondary voltage is achieved, and thus a discharge initiated. This high voltage was then transmitted via high voltage electrodes to the filter, where an electrical discharge occurred to ground, producing a regenerating affect within the filter.

This variable power supply configuration allowed the main discharge electrical variables such as discharge frequency, discharge voltage and power modulation (duty cycle) periods to be investigated.

4.4.2 Alternative Experimental Power Supplies

A number of methods to generate the high voltages at high frequency suitable for the Autoselective regenerative electrical discharge are commercially available. Of these methods the flyback transformer and driver circuit was tested in laboratory conditions to provide a more compact prototype power supply.

Flyback Transformer and Driver Circuit

Flyback transformers and drivers are a simple intrinsically low current (~30 mA) and therefore low power method to generate high voltages at high frequency (Kuffel et al, 2000). Flyback drivers are used extensively in TV and computer monitors (Hippler et al, 2001), providing constant frequency high voltages required for picture display. The extensive use of these systems has meant robust, inexpensive devices are readily available. Flyback circuits are essentially transistor driven devices (Figure
4-3); however, this does make them susceptible to over heating when forced to work above their rated power.

![Diagram of a typical single transistor flyback driver](image)

**Figure 4-3** - General circuit diagram of a typical single transistor flyback driver (adapted from Kuffel et al, 2000)

When sufficient power is supplied to the driver circuit, the transistor will conduct a current determined by the resistors $R_1$ and $R_2$ into the flyback primary. This current induces a current in both the secondary and feedback windings. The feedback current triggers the transistor to stop conducting, causing the magnetic field within the ferrite core to collapse. This rapid change in magnetic field produces an inductor-like action, providing a large voltage spike on the secondary windings, which is supplied to the load. The feedback current has ceased and, therefore, the transistor conducts once more to the primary windings. This cycle repeats at a natural frequency that tends to put the transformer into a resonant mode of operation. This resonance increases substantially the output voltage from the flyback driver and thus to the HV electrode of the Autoselective system.

Flyback transformers such as those shown in Figure 4-4 offer an energy efficient means to generate high voltages at high frequencies. Their widespread use in other applications, such as display screens, has meant that the technology has become
robust and relatively inexpensive, thus they provided an attractive option for Autoselective system prototype development.

Figure 4-4 – Flyback transformer and driver circuit to generate 12 kV pk at 20 kHz commonly used for display screen applications (PTI High Voltage Supplies, US, 2003)

4.5 Electrical Instrumentation

As with DC power, the instantaneous electric power in an AC circuit, with waveforms similar to those shown in Figure 4-5, is given by $P = VI$, where $V$ is the instantaneous voltage and $I$ is the instantaneous current.
Figure 4-5 - AC current and voltage waveform traces where the current leads the voltage by 10 degrees

The instantaneous voltage and current values at a time $t$ are given by:

\[ V = V_M \sin \omega t \quad \text{Equation 4-4} \]
\[ I = I_M \sin(\omega t - \phi) \quad \text{Equation 4-5} \]

where $V_M$ is the peak voltage, $I_M$ is the peak current, $\omega$ is the angular velocity, and $\phi$ is the phase difference between the current and voltage waveforms.

Thus the instantaneous power is given by:

\[ P = V_M I_M \sin \omega t \sin(\omega t - \phi) \quad \text{Equation 4-6} \]

Integrating the instantaneous power over a cycle or number of cycles and then averaging over the respective time period provides the average power (Warnes, 1994).

\[ P_{av} = \frac{V_M I_M}{2} \cos \phi \quad \text{Equation 4-7} \]

The term $\cos \phi$ is known as the power factor for the circuit. The term indicates the relative magnitude of the resistive elements to the magnitude of the reactive
elements (capacitive and inductive components). The power factor results in a reduction in the actual power delivered to the load compared to that which would be supplied to a purely resistive load supplied with the same voltage and current.

The phase angle between the Autoselective discharge current and voltage waveforms ranged from 0 degrees to 12 degrees, equating to a power factor ranging from 1 to 0.978. Such a phase difference and power factor reduces the power delivered to the load, in this case the discharge, by a maximum of only 3% compared to that delivered to a purely resistive load. The phase angle is believed to be due to capacitance introduced by the filter monolith ceramic between the HV and ground electrodes or between the discharge ground site and ground electrode. The capacitance appeared to vary between apparently similar filters leading to the various power factors. The variation was possibly due to small variations within the composition of the ceramic or some variation within the exact filter loading. Modelling of the electrical characteristics of the discharge and the filter system may provide further insight into the exact mechanism and influencing factors that introduce the capacitive elements into the discharge circuit, however, such work was not performed during the research discussed in this thesis.

The electrical discharge current and voltage waveforms were monitored and recorded using a Tektronix P6015A Digital oscilloscope. The oscilloscope digitised the waveforms and calculated the discharge power from the product of the current and voltage instantaneous values. Example Autoselective glow discharge current and voltage waveform traces are shown in Figure 4-6.
Figure 4-6 – Autoselective glow discharge waveform traces (Glow discharge generated using the inserted electrode configuration, under gas flow conditions)

The oscilloscope has a sampling rate of 2 GSs⁻¹, giving 100,000 samples per cycle when using a discharge frequency of 20 kHz and 20,000 samples at 100 kHz, thus the details of the waveform shape and characteristics can be recorded for analysis without being aliased.

The discharge voltage was measured using a Tektronix P6015A high voltage probe connected to the HV electrode. The probe was capable of measuring peak voltages up to 40 kV at a frequency of 75 MHz. The discharge current was measured using a Pearson 2877 current monitor on the HV cable supplying the HV electrode with an upper frequency limit of 200 MHz. The probe has upper current limit of 10 A but with a maximum sensitivity in the range 0.1 to 100 mA.

4.6 Cordierite Wall Flow Filters Used for Testing

A number of diesel particulate filters and materials have been described in published research (Xinyun et al, 2000, Cutler and Merkel, 2000, Wang et al, 2001,
Ohno, 2000, Hoj et al, 1995, Pattas et al, 2001). However, the most widely used technology to date is the ceramic monolith wall flow filter, used because of its high filtration efficiency and reasonably good resistance to the harsh environment of the diesel engine exhaust. Many filter regeneration systems discussed in research have used the Cordierite wall flow filters (Garner and Dent, 1989, Skoltsakis and Stanatelos, 1997, Pattas et al, 1997, Rumminger et al, 2001, Signer and Giorgio, 1989, Zikoridse et al, 2000, Barris and Rocklitz, 1989). Research of the Autoselective regeneration system detailed in this thesis mainly concentrates on the use of Cordierite, 100 cpsi, 0.0017 inch wall thickness filters produced from NGK Honeyceram. The HFR was designed to test the regeneration system on 5.66 inch (142 mm) diameter, 6 inch (152 mm) long wall flow filter monoliths. Larger monoliths (10.5" diameter by 12" long) are generally required on truck and off-highway engines of capacity greater than a naturally aspirated 3 l swept volume, in order to minimise backpressure from the large exhaust gas flowrates. The smaller filters were used on the HFR to minimise the size of gas blower and heater units required to generate representative flow velocities and temperatures for testing. The filters were supported and gas sealed within the canister by commercially available flexible exhaust gasket matting called Interam® manufactured by 3M.

The hot flow rig provided a means to test the effectiveness of the Autoselective system in regenerating a wall flow filter under controllable exhaust like gas conditions whilst monitoring the electrical characteristics of the discharge. The following sections discuss the methods used to evaluate regeneration effectiveness including a novel method developed to assess the impact of regeneration on the local backpressure profiles within the wall flow filter.
4.7 **Filter Loading and Regeneration Assessment**

Regeneration of a particulate filter is the removal of the PM trapped within the filter. This process results in a reduction in the overall mass of the filter system from the loaded state to the clean state and, simultaneously, a reduction in the restriction to gas flow or backpressure. These charges to the filter system caused by regeneration may be used to assess the effectiveness of the regeneration process using a variety of techniques, some of which are discussed further in the following sections.

A number of methods to analyse a filter after regeneration have been discussed in published research. These include weighing the filter before and after regeneration (pre- and post-weighing), monitoring concentrations of gaseous carbon components such as CO$_2$ during regeneration to produce a carbon balance (Matsui et al., 2003, Yamamoto et al., 2003), monitoring the pressure drop across the filter (Nixdorf et al., 2001, Kelly et al., 2003, Stratakis and Stamatelos, 2004, Psarianos et al., 2002, Konstantas et al., 2003) and dissection of the filter to allow visual inspection to find any effect on the filter ceramic structure such as thermal damage (Garner and Dent, 1990). The assessment methods each provide different information to various degrees of accuracy about regeneration and the impact on the filter.

### 4.7.1 Pre and Post Regeneration Mass Measurement

Regeneration reduces the mass of PM within the filter and thus the overall mass of the filter compared to that prior to regeneration. Measurement of the mass change caused during regeneration has been used to assess regeneration effectiveness by a number of researchers (Scott-Sluder and West, 2000, Mayer et al., 2000, Barris and Rocklitz, 1989). Gravimetric measurement provides a simple and rapid assessment of regeneration. As with most measurement techniques, sources of error may be introduced such as moisture absorption and desorption or mass loss through abrasion during handling. Errors in mass change due to moisture absorption are avoided by heating the filter to 150 °C for 15 minutes prior to weighing thus
ensuring all moisture is evaporated. The filter section is then weighed without being allowed to cool significantly thus preventing water vapour from atmospheric humidity condensing onto the filter.

A clean 5.66 inch diameter, 6 inch long, 100 cpsi Cordierite wall flow filter weighs approximately 1200 g. An analytical balance capable of measuring such a large mass has a relatively low resolution of approximately 0.01 g. The mass change during regeneration using a single HV electrode was expected to be small relative to the overall mass of the filter. Thus a high-resolution technique was required to accurately measure the mass change during regeneration and allow detection of any changes caused by the variables being investigated such as flowrate and gas temperature. However, a balance with the required resolution has a low maximum weight capacity of around 200 g. Thus a small test section, approximately 50 mm x 50 mm in cross section (Figure 4-7(a)), of a loaded filter was used as a test piece for a single HV electrode. This small section had a mass of around 170 g, which could be measured using an analytical balance with the required high resolution. This allowed detection of changes in regeneration rate caused by alteration of the gas variables under test.
Figure 4-7 – Test section of wall flow filter to allow high resolution gravimetric assessment of regeneration (a) test section of wall flow filter, (b) schematic of test section with support structure and gaskets

The test section was carefully cut from the loaded filter, ensuring minimal damage to the section perimeter walls and minimal contact was made with the test section ensuring the trapped PM underwent minimal disturbance. Ceramic dust created by the cutting process was removed via a low power vacuum dust extraction unit during sectioning.
The test section was held in a support structure constructed from a loaded wall flow filter (Figure 4-7(b)). This porous support structure minimised the differences in flow patterns between the test condition and those within a normal wall flow filter. Interam® exhaust gasket matting was used to provide a gas seal between the test section and the support structure, which ensured there was not a 'low restriction' path for exhaust gases to pass through the filter structure.

The 50 mm x 50 mm filter test section was weighed prior to regeneration and after regeneration using a Sartorius RC210D research balance with a resolution of 0.0005 g and an upper limit of 195 g.

A pressure map (discussed in detail later in Chapter 4) of the channels within the supported test section and those of the central section of a complete wall flow filter was taken. The pressure map indicates the relative velocity of the flow through the individual outlet channels. This allowed detailed, channel-by-channel analysis of the local backpressure and details of the flow patterns through the filter.

Figure 4-8 illustrates the results from pressure mapping of the supported test section and pressure mapping of a similar central region within a complete wall flow filter.
Figure 4-8 - Wall flow filter test section pressure maps (a) central region of solid wall flow filter, (b) supported test section. Units: Pa

The pressure maps in Figure 4-8 show no significant difference in the local backpressure or axial flows through the outlet channels of the test section and those of a complete filter. The gasket that provided a gas seal is clearly evident but this small region appears to have no effect on the centre region of the test section where controlled regeneration tests were conducted. The centre test section supported in the structure had a uniform backpressure and gas exit velocity profile. Thus the test section supported in the wall flow structure allowed regeneration of the small section of loaded filter without changing significantly the flow conditions under which the Autoselective discharge was operating. This method of regenerating small test sections allowed high-resolution mass measurement to be used to assess small changes in regeneration rate.
4.7.2 Assessment of Potential Errors Introduced by the Test Procedure

The experimental procedures used with the filter test section were tested to assess the magnitude of experimental errors introduced. Eight runs were conducted where a PM loaded filter test section was heated to 150 °C, weighed, then fitted into the support structure and inserted into the hot flow rig. The rig gas parameters including increased water vapour and reduced oxygen concentration were set and allowed to stabilise. The conditions were maintained without any regenerative discharge being operational. The gas conditions were then returned to 150 °C ambient air for 10 minutes to remove absorbed moisture. The filter test section was then removed and weighed whilst hot to establish any changes in weight caused by the experimental processes. The largest mass change was 0.0045 g, with an average over the eight runs of 0.0035 g.

The smallest pre to post regeneration mass difference measured during testing (discussed in Chapter 5 and Chapter 6) was 0.1555 g. Therefore the average difference introduced by the experimental process of 0.0035g, represents just 2.25 % of the smallest measured pre-post mass difference. The use of small test sections of loaded filter was an adequate process to 'gravimetrically' assess small levels of regeneration to a high resolution without introducing errors that could mask the affects of the factors under investigation.

4.7.3 CO₂ and CO Monitoring

As discussed in Chapter 1, PM mainly consists of carbon which is oxidised during regeneration using the Autoselective discharge. Measurement of the concentration of carbon compounds within the exit gases from the hot flow rig allows chemical analysis of the combustion process to estimate the amount of carbon oxidised during regeneration. Assuming the combustion process to mainly consist of the following reactions:
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\[ C + O_2 \rightarrow CO_2 \quad \text{and} \quad 2C + O_2 \rightarrow 2CO \]

Measurement of \( CO_2 \) and \( CO \) concentrations within the gases from the hot flow rig allows calculation of the mass of carbon oxidised per unit time. The carbon compound concentration was measured using a Pfieffer Thermostat mass spectrometer.

### 4.7.4 Mass Spectrometers

A mass spectrometer is a device that measures accurately the volumetric concentration of the constituents of a gaseous or vapour mixture. A mass spectrometer provides the means to assess the concentration of specific components, such as \( CO_2 \), in a gas stream such as that produced by the HFR.

A Pfieffer Thermostat mass spectrometer was used to investigate the gases produced during filter regeneration by the Autoselective discharge. The mass spectrometer was capable of monitoring \( CO_2 \) volumetric concentrations with a resolution of 10 ppm. The ambient atmospheric concentration of \( CO_2 \) is on average 370 ppm, but fluctuates due to seasonal changes in plant growth by around 10 ppm. Preliminary regeneration tests using gravimetric analysis indicated the oxidation rate produced by a single HV electrode to be approximately 0.6 g.hr\(^{-1}\). Assuming at this stage that all of the carbon is oxidised to \( CO_2 \), this regeneration rate under flowrates similar to those of an engine operating at high speed would produce a \( CO_2 \) concentration of around 30 ppm. The measured value is close to that of the resolution of the mass spectrometer and as such would make investigation of factor influences impossible.

Whilst the mass spectrometer method was not suitable for assessing the average regeneration performance that was under investigation in much of this research, it could provide a good means to validate gravimetric measurements. Alongside this, moving the point at which the mass spectrometer was sampling the gas flow enabled investigation of trends in regeneration rate against time with greater
resolution than that provided by gravimetric analysis. This provided valuable information in the development of the potential operating strategies to maximise regeneration whilst minimising power input or the number of HV electrodes required per unit filter size.

As mentioned earlier, mass spectrometers, their use and limitations are discussed in greater detail in Chapter 6 during the description of the investigation of the Autoselective regeneration rate using the Pfieffer Thermostar mass spectrometer.

4.7.5 Filter Pressure Mapping and Analysis

Regeneration systems aim to remove the trapped PM from the filter surface to return the backpressure to the clean filter levels. A single HV electrode of the Autoselective system was only capable of regenerating a small section of the entire filter. This localised regeneration lead to regions of low backpressure and even backpressure variations between neighbouring channels. These local backpressure variations lead to maldistribution in the flow through the filter. Investigation of the local backpressure variations allowed the effectiveness of regeneration to be assessed and also provided information concerning how regeneration progressed. The area of filter affected by the regeneration system can be measured along with patterns within this region.

The relative flow rate through individual outlet channels of a wall flow filter within the hot flow rig could be evaluated using a small Kiel probe (outer diameter 1 mm), with the flow straightening outer shroud removed (Figure 4-9(a)). The probe was inserted 8 mm into the outlet channel (Figure 4-9 (b)), thereby it did not extend beyond the rear wall flow filter channel end plugs, ensuring all gas flow through the outlet channel was measured. A Kiel probe measures the stagnation pressure of a moving fluid. The higher the stagnation pressure, the higher velocity of the fluid when it was flowing and thus the larger the flowrate of the fluid passing through that individual channel compared to others within the same filter. The probe was
connected to a calibrated Furness Controls FC012 digital manometer, with a 1 Pa resolution.

![Image of a digital manometer]

Figure 4-9 – Pressure mapping assessment of local backpressure changes caused by regeneration using the Autoselective system (a) 1 mm diameter Kiel probe (without shroud), (b) probe inserted into an outlet channel of the wall flow filter

The size of the Kiel probe (diameter 1 mm) compared to the size of the filter channel means this method is not suitable for accurate measurement of the actual gas velocities within the filter. The presence of the relatively large Kiel probe in the channel will cause changes in the flow patterns making quantified velocity measurements inaccurate. However, the disturbance caused by the Kiel probe is very similar in each channel. Thus, the technique provided results that allowed comparison of flowrate through individual channels identifying backpressure patterns and allowing analysis of the relative effects of regeneration across the filter under various conditions.
The total gas flow rate and temperature during pressure mapping are kept constant to allow different regeneration tests conducted on the same filter to be compared. Variations in total gas flowrate or temperature during pressure mapping would lead to changes in the flowrate through the outlet channels and thus introduce errors into the comparative data between regeneration sites.

Comparisons between different filters are not possible, since the flow through any particular filter region is in part determined by the regeneration in other regions of the same filter. For example, if a region of the filter is regenerated very effectively, thus presenting a low local backpressure, then a significant proportion of the total flow will pass through this clean region. This preferential flow reduces the flowrate, and thus the stagnation pressures measured by the Kiel probe, through all other regions of the same filter. Therefore, the pressure mapping analysis technique is only useful in determining the relative effectiveness of regeneration tests conducted on the same filter.

Pressure mapping does not completely analyse the filter structure post regeneration. If the filter has been damaged during regeneration any holes within the filter wall will allow high local flowrates to develop. These high flowrates may be mistaken for areas of regenerated filter. The pressure mapping does not allow areas of partially regenerated filter to be differentiated from areas of regenerated filter that have also been damaged. Thus, following regeneration and pressure mapping, if there is any possible damage the filter structure should be inspected either by sectioning or possibly using an endoscope or borescope.

4.7.6 Post-Regeneration Filter Dissection

The Cordierite wall flow filter test pieces may be sectioned to allow assessment of regeneration, regeneration patterns and moreover any damage caused to the filter structure by the regeneration mechanism. Filter test pieces were sectioned after
being regenerated by the inserted electrode configuration (discussed in Chapter 6), and subsequent pressure mapping. Filters were carefully sectioned with a 0.4 mm ceramic saw, through the plane containing the central inserted HV electrode channel, as this was identified as the region where damage occurred in preliminary testing of some electrode configurations. Care was taken to ensure the blade did not contact the two walls to be examined during sectioning, therefore causing minimal disturbance to any evidence of regeneration or damage. The ceramic dust produced during sectioning was carefully removed with a low-pressure vacuum extraction unit.

Post-regeneration sectioning allowed close examination of the filter for changes in the monolith structure, assessment of regeneration effectiveness and identification of patterns within the filter regeneration.

### 4.7.7 Filter Loading and Regeneration Assessment Techniques Summary

A number of methods suitable for assessing the loading of a wall flow particulate filter are available. These methods can also be used to assess regeneration effectiveness after testing. A technique was developed to allow high-resolution gravimetric analysis of small changes caused by partial regenerations when using a single HV electrode. A carbon balance approach can be used to estimate the quantity of carbon oxidised during regeneration through gas analysis using a mass spectrometer. A novel flow analysis method was developed to evaluate changes in local backpressure caused by regeneration experiments conducted on the same filter. Filter dissection allowed the investigation of changes to the monolith structure caused by the regeneration mechanism.

Overall, the effectiveness of the regeneration system in oxidising PM could be assessed along with changes to filter backpressure profiles and the filter structure. These methods allowed assessment of the performance of the regeneration technique and its impact on the filtration system.
The following section of this chapter summarises the general procedure used to investigate the performance of the Autoselective system in regenerating a wall flow filter under various conditions within the HFR.

### 4.8 Regeneration System Testing Procedure

Clean Cordierite wall flow filters were loaded on a dynamometer controlled 4 litre Perkins 1100 series turbocharged, aftercooled DI diesel engine that is representative of the small heavy-duty commercial engines coming under the increasingly stringent emissions legislation discussed in Chapter 1. The majority of filters were loaded to between 1.5 g.l\(^{-1}\) and 4 g.l\(^{-1}\) although the system was tested at higher loadings of up to 8 g.l\(^{-1}\).

The exact pre-regeneration filter loading was measured gravimetrically under controlled conditions. The filter test section was then regenerated in the stable test conditions under investigation for a set period. The regeneration achieved during the test period can be measured via a number of means that were discussed earlier in this chapter.

The average discharge electrical power supplied during the test period was calculated from the voltage and current characteristics of the operating discharge monitored using the digital oscilloscope.

The measured data of the regeneration achieved and the discharge electrical power supplied allowed analysis of how effectively the Autoselective discharge performed under various conditions. Comparative assessments included the calculation of the regeneration rate (g.hr\(^{-1}\)) and the regeneration efficiency (grams of PM oxidised per unit time per unit of discharge power supplied, g.kW\(^{-1}.hr^{-1}\)), and how the filter backpressure was affected by the regeneration system.
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The above experimental procedure was used to investigate the response of the discharge power and regeneration rate to changes in a number of experimental factors and system variables. However, the number of variables that were identified to potentially influence the Autoselective system performance was sufficient to make basic investigation techniques unacceptable in terms of the time required for completion.

The final sections of this Chapter discuss the statistical techniques, known as Design of Experiments, which were developed during the 20th century and used in this research to facilitate efficient investigation of systems and processes.

4.9 Design of Experiments Techniques

A complete investigation of the four major exhaust gas characteristics discussed earlier in this Chapter, where each factor was tested at three levels to identify any curvature within the response would require a minimum of 81 separate experiments ($3^4 = 81$). The experimental data gathered would still not be complete. Verification of the experimental procedure and data obtained would be required by repetition of part of the experimental set or the insertion of replicate points. Replicate points are experimental points that are conducted more than once, to allow estimation of the pure experimental error and the repeatability of the procedure. A replicate point is not simply a repeated measurement. The experimental factors must be individually reset and the complete experiment run be completed again to enable the variation or experimental error to be assessed. Thus the total time to investigate the Autoselective, using a standard experimental technique where each variable is systematically changed, was considered unacceptable.

An interaction occurs when the level of one factor affects the influence that another factor has on the measured response. For example, if the gas temperature was found to cause a given change in the response when the flowrate was low, and a different change under high flow rate conditions; then the gas temperature and flow rate are
said to interact to determine the measured response. DoE techniques are able to identify factor interactions within the developed experimental matrix.

4.9.1 Design of Experiments (DoE) Principles

Design of Experiments (DoE) techniques were developed to facilitate a systematic approach to investigate a problem or system, providing statistically analysed results. This analysis can provide measures of both the main effects and factor interactions on the response, along with estimates of their statistical significance. The analysis technique used in DoE involves the development of a mathematical model or response surface, linking changes in experimental factors to changes in the measured response. The statistics of the variance between the model and experimental data is then calculated. The model, if acceptably accurate to within predetermined confidence limits, can be used to predict optimum factor levels to improve system performance.

4.9.2 Development of DoE

Sir Ronald Fisher was the main innovator in the use of statistical methods in experimental design at the Rothamsted Agricultural Experiment Station in London (Myers and Montgomery, 2002). Fisher developed and first used the analysis of variance (ANOVA) as the primary method of statistical analysis in experimental design. Since Fisher's pioneering work, there have been a large number of other significant contributors to DoE literature including R. Myhers, G. Box and probably most popularly known G. Taguchi. Taguchi is credited with much of the practical use of experimental design techniques in industrial and production applications to minimise variance and achieve process robustness.
4.9.3 DoE Techniques

Within DoE there exist a number of established or set designs that can be used to achieve certain experimental objectives. For example factorial designs can generally be used to identify vital factors that affect a process, in simple screening investigations. Within the factorial designs, a number of experimental matrices have been developed for use in investigations of various numbers of factors. The full factorial design is used when all possible combinations of factors are to be tested, however, this leads to a large experimental matrix, which can place excessive demands on resources. Fractional factorial designs allow more factors to be tested in a reduced number of experimental runs than the full factorial designs. However, fractional factorial designs introduce aliasing. Aliasing occurs when interaction affects between main factors cannot be conclusively separated within the experimental data. Such designed experiments are only used when there is substantial previous knowledge of the process, which suggests that factor interactions do not occur.

Taguchi methods or matrices are a subset of factorial designs, often using factors to be tested at three levels. Testing at three levels allows curvature within the process response to be identified. If a factor is only tested at high and low levels then the response at points between these levels is unknown (Figure 4-10). Testing at three levels, high, medium and low, allows improved estimation of the factor affects throughout the design space and assesses curvature of the response.
Chapter 4 - Research and Experimental Techniques

Figure 4-10 - (a) Testing a factor at only two levels does not show curvature in the response measured. (b) Testing at three levels allows identification of response curvature and thus a more complete investigation of the design space.

However, Taguchi experimental designs all contain some level of aliasing. Interactions between two main factors cannot be determined using standard Taguchi designs. This significantly limits the application of the Taguchi experimental designs in a number of applications where interactions are often expected to occur such as chemical process and internal combustion engine processes. As such, the widely known Taguchi designs are not useful for most engineering research, such as the Autoselective system under investigation here.

An alternative to factorial designs is the Response Surface Method (RSM), which was developed to create an equation or model of the response as a function of the levels of the factors under investigation. The response surface generated (see Figure 4-11) can then be used to analyse and optimise settings to refine system performance. Contour plots are often generated to illustrate response surfaces (see Figure 4-11).
Research and investigation of novel processes is often carried out through a series of RSM matrices. Screening studies are conducted in early experiments to eliminate factors that have no influence on the response. The list of candidate variables may be reduced so that subsequent experiments can be more efficient and require fewer runs or tests to provide a complete Response Surface. In many cases a first or second order model is used as the basis of experiment design. First order models are likely to be appropriate in approximating the true response surface over a relatively small region of the variable space in a location where there is little curvature. Such models are sometimes called main effects models because they are unlikely to include interaction effects. If there is an interaction between the main variables it can be added to the model and this then introduces the curvature to the response function (Myers and Montgomery, 2002). However, if the curvature of the true response surface is sufficient, then the first order model, even with the interaction term included, is inadequate. A second or possibly third order model is then required to accurately determine the curvature and the response surface shape. The terms within the higher order models are estimated through linear regression analysis of the data collected during experimentation. A number of computer packages are now commercially available to perform the regression analysis for model development to the required number of significant figures (QD Consulting Training Manual, 2003).
and the subsequent plotting of the calculated response surface. The package StatEase Design Expert v 6.0.10 was used in this research due to its industrial validation and acceptance in internal combustion engine research.

Within Response Surface Methods (RSM) a number of experimental designs are available which can be used to collect the data required for screening and model development. The designs vary in the efficiency with which they are able to calculate the model terms. Different experimental designs require different numbers of test runs to be completed in order to calculate the model terms. For example a designed experiment with four factors tested at three levels using a factorial design would require 87 experiments (81 experiment runs and 6 replicate runs for experimental error assessment). A Box-Behnken design is capable of producing the same response surface from data collected from just 29 runs including replicate points (StatEase v.6.0.10, 2005). The Box-Behnken design is only capable of developing second order response surfaces. However, more importantly for many investigations all of the experimental points developed by a Box-Behnken design are positioned at the centre of the edges on the design space (see Figure 4-12). This selection of points means that the experimental design is confined to situations in which one is not interested in accurately predicting response at the extreme values of the various factors (see Figure 4-13) (Myers and Montgomery, 2002). In many situations these are the points in the design space in which the investigator is most interested to assess system performance, including the Autoselective system research. Investigation of the performance of the Autoselective discharge at the extreme values of the gas characteristic factors is considered important. As such the Box Behnken design was unacceptable.

![Box Behnken design points positioned at the centre of the edges of the design space](image)
Alternative experimental designs within RSM include the standard Central Composite Design (CCD) and the various Optimal Designs. CCDs and Optimal Designs produce second order response surfaces and are both highly efficient in minimising the number of experimental runs required for model development. CCDs are set format designs (see Figure 4-14) similar to the Box Behnken design. A group of set points within the design space are tested.

However, the rigidity of such set designs create circumstances where the use of CCDs is limited due to the presence of non-achievable points in the experimental design space. Such points, at which tests cannot be physically conducted, leave holes within the response data thus limiting the accuracy of any subsequently developed model. Alongside this, the CCD does not provide experimental runs at the extreme values of the experimental factors (see Figure 4-14), which, as previously stated, are often of great interest to the researcher. Optimal Designs offer flexibility in the initial experimental design stages. The use of Optimal Designs has become commonplace.
with the development of computer packages to run the algorithms that generate the experimental matrices to match the specific optimality criteria selected. D-Optimal designs have become most popular due to the relatively simple computation (Myers and Montgomery, 2002). D-Optimal designs create a candidate list of experiments and then select runs, which together fulfill a statistical mathematical algorithm. The general operation of the algorithms will only be briefly described here but further information concerning the fundamental theories and mathematics can be found in a number of references including Myers and Montgomery (2002). Generally the design algorithm starts with a set of points that allows the estimation of model parameters, then a process of design augmentation initiates. A random initial design point is selected and augmentation occurs through the selection of the next point from the candidate set that is most appropriate for improving the current design prediction until the D-Optimal criterion is achieved. D-Optimal designs do have disadvantages. For examples the user must indicate a model type during the design stages that the response surface is believed to follow. However, often the model type is not known in the early stages of research. If the model type fitted during data analysis is not that which was input during the design process then the experimental design is unlikely to meet the chosen Optimal criteria. In the worst case when a lower order model has been predicted during the design stage than is actually required, there will be insufficient data available to build a non-aliased model. If a higher order model has been predicted than is actually necessary then the same response surface model coefficients could have been gathered more efficiently from a smaller number of experiments.

The flexibility in the experiment development stages and the highly efficient matrices developed were the main considerations in the decision to use D-Optimal design matrices for the investigation of the Autoselective discharge system's performance in regenerating a loaded diesel wall flow filter.
4.10 Concluding Remarks

This chapter has discussed the development and research of apparatus and experimental techniques that allowed investigation of the Autoselective system’s performance in regenerating diesel wall flow filters, including:

1. a hot flow rig (HFR) designed to provide a controlled and stable environment in which loaded diesel wall flow filters could be regenerated in exhaust like conditions;
2. research and development of a number of techniques that allowed the effectiveness of the regeneration process to be evaluated and quantified, such as pre- and post-weighing, CO₂ monitoring and filter pressure mapping; and
3. DoE techniques were researched and used to maximise time efficiency of data gathering and analysis.

The investigations conducted using these techniques and apparatus is discussed in the following chapters of this thesis and provided a basis from which a prototype system was developed for on engine testing and performance validation.
5 Autoselective Discharge Fundamental Performance Investigation

The research detailed in this chapter concentrates on the investigation of the fundamental variables that influence the operation of the Autoselective discharge in oxidising PM and its behaviour in exhaust like flows. The regeneration system development towards a practical solution for use with a Cordierite wall flow filter will be discussed along with the subsequent on-engine testing of the prototype system in Chapter 6. This thesis does not include a detailed investigation or development of the power supply for the Autoselective discharge system. The power supplies used in the investigation were of experimental and early prototype nature suitable for laboratory research work.

The Autoselective electric discharge was generated by a high frequency, high voltage source connected to a suitable electrode configuration. The use of high frequency, compared to the filter regeneration systems using DC plasma, enables the high voltage required for breakdown to be achieved using small ferrite transformers. Once generated, the discharge is attracted to the electrically conducting...
agglomerated PM trapped on a ceramic wall flow filter. The particles are oxidised by the discharge, regenerating the filter, and then the discharge moves to the next conducting site or extinguishes until the filter collects more PM. Electric discharges have an inherent tendency to determine their path of lowest impedance to ground, but the exact mechanism by which they do this is not understood (Meek and Craggs, 1978, Hippler et al, 2001). This selection of the lowest impedance path provides the discharge with its Autoselective characteristic, enabling the PM to be selected from the insulating filter surface.

5.1 Investigation of the Fundamental Aspects of the Autoselective Discharge

The oxidation of PM by an electric discharge is likely to be affected by a number of variables including the type of discharge and the frequency of the alternating voltage. The environment in which the discharge operates may also impact performance of the discharge and the oxidation mechanism. This chapter therefore discusses work that was conducted to answer the two following important fundamental questions:

1. What discharge characteristics were influential in determining the PM oxidation rate?

2. Could the discharge be generated under exhaust like flows, and if so, what were the effects of such flows on the discharge behaviour and regeneration characteristics?

These investigations allowed identification of the discharge characteristics that maximise the regeneration rate achievable and aid the assessment of the potential for the Autoselective system to be used to regenerate diesel filters in production engine systems.
5.2 Discharge Regime Investigation - Autoselective Discharge
Type Selection

As discussed in Chapter 3, there are a number of different types of electric discharge or discharge regimes. Electric discharges are primarily differentiated by their current and voltage characteristics dictated by the electrode configuration, background gas characteristics and type of power supply. Different electrical discharges exhibit differences in optical appearance and plasma characteristics, such as current density and particle energies. These various characteristics mean that discharges of different types are best suited to specific applications as discussed previously in Chapter 3. The optimal discharge for the Autoselective system would provide maximum regeneration rate, for a minimum power input, whilst not damaging the filter structure and be stably generated under exhaust flow conditions using, what engine manufacturers would deem, a practical power supply.

5.2.1 Discharge Regime Experimental Configuration

Initial investigation of the oxidation performance of the three major types of ac atmospheric discharge (i.e. glow discharge, corona discharge and dielectric barrier discharge) was conducted using a single pin electrode or dielectric covered plane operating in quiescent ambient air on a preloaded wall flow filter. Once the oxidation performance had been assessed, the discharge stability under exhaust like conditions was investigated to ensure the discharge could operate in the diesel exhaust gas flow environment.

A flyback transformer power supply, as previously discussed in Chapter 4, provided the alternating, high voltage at 20 kHz to a single electrode, in a similar fashion to the investigations in the preliminary feasibility study. The high voltage power supply and given electrode configuration caused an electrical discharge producing plasma of the specific type under study. The discharge voltage and current were measured and recorded using the high-resolution digital oscilloscope described in
Chapter 4. The average discharge power was calculated from the product of the current and voltage time traces. The discharge type was confirmed from the voltage and current trace profiles and the physical appearance of the plasma as discussed in Chapter 3.

The investigation used a copper pin electrode, with a filter test section positioned on a ground plane, in quiescent ambient air as illustrated schematically in Figure 5-1.

![Figure 5-1- Schematic of the experimental pin electrode arrangement for discharge investigation](image)

The type of discharge generated in the electrode gap was determined by the electrode set-up (i.e. gap and configuration) and the power supply operating point. The glow discharge was generated when the pin electrode (y) was 5-6 mm from the filter sample. Extending the gap between the pin electrode and the filter sample to 14-18 mm allowed a corona discharge to be generated. The gap required to maintain the corona discharge reduced as the regeneration progressed and thus small alterations were made using a screw adjustable platform to maintain the discharge within the corona regime. Alternatively the discharge could also be made to enter the corona regime through the reduction of the supply voltage under the correct electrode set up. However, such a discharge control method did not allow the discharge power to be adequately varied with the flyback experimental power supply to assess the effect on regeneration rate. The dielectric barrier discharge (DBD) was generated using a plane electrode with a polycarbonate dielectric.
applied. The DBD was a volume discharge, filling the gap between the electrode and the filter section. The electrode area covered by the DBD maintains the current (energy) density \( \text{J.m}^{-3} \) for a given background gas and condition. Increasing the discharge power allowed the discharge to cover a larger area until the whole electrode is covered. Subsequent power increases resulted in short duration increased local currents and electric field variations until the dielectric barrier was overcome and a single discharge breakdown stream was initiated between the two metallic electrodes.

The input voltage to the power supply was set using the power amplifier. The input voltage was directly proportional to the power of discharge produced, however, the type of discharge generated determined the actual discharge power. The flyback power supply was provided with 80 V for relatively low power discharge tests. Setting the input voltage to 110 V provided relatively high power discharges for testing. Preliminary tests demonstrated that when the input voltage to the experimental power supply fell below 80 V, stable discharges could not be maintained.

5.2.2 Discharge Regime Selection Results

The regeneration rate and efficiency of the various types of discharge was assessed using the method described above. The power supply was set to produce a stable discharge of the type under test, whilst the discharge current and voltage traces were recorded on the oscilloscope for power analysis. Table 5-1 summarises the data obtained from the investigation. It should be noted that the test using a relatively high power glow discharge was stopped after 18 minutes since the discharge became unstable and entered the corona regime. The discharge had oxidised almost all of the PM from the test section and this then altered the electrical circuit to ground to the extent where the discharge could no longer be maintained in the glow regime. Once the mass of PM fell below that required to sustain a discharge, the discharge changes regime or extinguished, showing similar Autoselective
characteristics observed during the initial feasibility study conducted by Harry et al (1999).

<table>
<thead>
<tr>
<th>Discharge Type</th>
<th>Time (mins)</th>
<th>Input Voltage (V)</th>
<th>Discharge Power (W)</th>
<th>Regeneration Rate (g/hr)</th>
<th>Discharge Power Regeneration Efficiency (g/kW·hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glow</td>
<td>20</td>
<td>80</td>
<td>10.26</td>
<td>0.399</td>
<td>38.89</td>
</tr>
<tr>
<td>Glow</td>
<td>18</td>
<td>110</td>
<td>14.01</td>
<td>0.553</td>
<td>39.50</td>
</tr>
<tr>
<td>Corona</td>
<td>20</td>
<td>80</td>
<td>5.68</td>
<td>0.051</td>
<td>8.98</td>
</tr>
<tr>
<td>Corona</td>
<td>20</td>
<td>110</td>
<td>7.26</td>
<td>0.066</td>
<td>9.09</td>
</tr>
<tr>
<td>DBD</td>
<td>20</td>
<td>80</td>
<td>28.56</td>
<td>0.003</td>
<td>0.11</td>
</tr>
<tr>
<td>DBD</td>
<td>20</td>
<td>110</td>
<td>39.23</td>
<td>0.006</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Table 5-1 - Discharge investigation summary

The DBD was found to be the most efficient discharge generated with the experimental power supply. Only approximately 5% of the supplied energy was lost within the power supply during DBD generation. However, the glow and corona discharge generation experienced significant inefficiencies, 65% and 80% of the power was lost respectively, due to the particular design characteristics of the flyback power supply used. The characteristics of any eventual production power supply could be tailored to the particular discharge that is selected to maximise conversion of supplied power into discharge power for PM oxidation. At this stage the study focused on the rate at which PM was oxidised and the efficiency with which the discharge power was used in the oxidation process.

Figure 5-2 shows clearly that the glow type discharge has significantly higher regeneration rate and discharge power regeneration efficiency compared to the corona and DBD discharges under study. The glow discharge was capable of oxidising a significantly larger mass of PM per unit time than the corona or DBD type discharges using the single pin electrode configuration tested. Under relatively high power discharge conditions the glow discharge could oxidise in excess of 7 times the mass of PM per unit time compared to the relatively high power corona discharge. The regeneration efficiency of the glow discharge was also over 4 times higher than that of the corona and 250 times that of the DBD discharges (see Figure 5-3).
Figure 5-2 - Regeneration rates of various discharge types investigated at high and low relative discharge powers (data from Table 5-1)

Figure 5-3 - Regeneration efficiency of discharge types investigated (data from Table 5-1)
5.2.3 Discharge Regime Analysis

The DBD transferred approximately 30 W of power whilst only oxidising an average of 0.005 g of PM per hour. The high-energy demand was due to the large number of pulses per cycle. Each pulse only contained a small amount of energy, approximately 0.1 mJ, but there were an average of 200,000 to 300,000 pulses per second. The short duration of each pulse appeared to be insufficient to cause PM oxidation.

The regeneration rate of the DBD was calculated to change by over 50 % between the high and low power tests. However, the very small mass changes caused during regeneration meant that the errors introduced by the gravimetric assessment process, discussed in Chapter 4, were likely to be significant in the regeneration rate and efficiency calculations. The investigation showed that the regeneration efficiency of the DBD was approximately 250 times lower than that of the glow discharge under investigation. The energy required to oxidise 5.5 g.hr⁻¹ of PM was 36 kW, making the DBD impractical for further consideration.

The corona discharge comprised a series of short duration filaments with rise times of less than 20 ns. However, the corona discharge only had a single pulse per half cycle. Each filament had a large current (> 10 A) compared to the DBD but each pulse only contained around 0.3 mJ of energy. The large number of low energy, short duration pulses per unit time was believed to limit the regeneration rate achievable similar to under the DBD regime. Increasing the amount of energy per pulse lead to an increase in regeneration rate but this was difficult to achieve under the atmospheric pressure conditions and limited power supply characteristics, rendering it impractical for this application. Increasing the operating frequency of the corona discharge would increase the number of pulses per unit time and thus should lead to an increased regeneration rate. However, assuming the regeneration rate of each pulse to remain at the level observed at 20 kHz, a discharge operating frequency of approximately 154 kHz would be required to oxidise the same mass of PM per unit time as the glow discharge. Again assuming the energy contained in
each pulse was the same as that observed at 20 kHz, the 154 kHz operating frequency would deliver approximately 92 W of discharge power to oxidise the PM. The influence of discharge frequency is discussed in later sections of this chapter, but at this stage such high frequency supplies were not as desirable from an economic point of view as the more commonly available, highly developed 20 kHz supplies for display screen applications.

The atmospheric pressure alternating glow discharge operating in air had current and voltage traces that were in close phase and that did not contain large numbers of filamentary or short rise time components (see Figure 5-4). The discharge energy was delivered throughout the cycle rather than being comprised of a number of short duration pulses as with the DBD and corona discharges.

![Glow Discharge Voltage (kV) vs. Glow Discharge Current (mA)](image)

**Figure 5-4** - Glow discharge current and voltage traces from basic pin electrode operation in quiescent, ambient air (Pin electrode to PM (ground) separation $y = 15$ mm)

Further investigation of the glow discharge showed that increasing the discharge power produced a linear increase in the regeneration rate (see Figure 5-5), however, the regeneration efficiency remained constant (see Figure 5-5).
Figure 5-5 - Regeneration rate and regeneration efficiency of the glow discharge operating at various discharge powers

When the discharge power was increased above 22 W under quiescent air conditions the discharge was observed to cause significant heating of the filter test section. The ceramic filter was caused to glow in the region of the discharge root where regeneration was occurring. Once the discharge moved to the next regeneration site the filter section had taken on a glistening or glass like appearance. Examination of the wall flow section after testing showed that the surface of the ceramic had become fused or 'glassed' (see Figure 5-6), indicating the temperature had been sufficient to cause the ceramic structure to melt. This fusing modification of the filter surface would prevent these regions from contributing to the filtration mechanism. Alongside this, the damage indicated highly localised heating which was likely to introduce considerable thermal stress into the ceramic structure thus reducing fatigue life. Both consequences meant that this thermal damage was unacceptable.
The regeneration rate for the glow and corona discharges was found to be dependent upon the discharge power. All experiments showed that increasing the discharge power increased the regeneration rate. However, the regeneration efficiency remained almost constant. Therefore, it could be concluded that increasing the energy within the discharge could increase the mass of PM that can be oxidised per unit time. However, the efficiency with which this energy was used was constant within the range tested for a given discharge. Increasing the discharge power will increase regeneration rate, however, the on-set of thermal damage to the filter described above limits the power that could be applied through the glow discharge. No thermal damage was observed during the testing of the corona discharge, indicating that increasing the power above those levels tested in the investigation could lead to an increase in the regeneration rate achieved. However, the regeneration efficiency of the corona discharge was significantly less than that of the glow discharge, thus further Autoselective investigation and development centred on using the glow discharge.

5.2.4 Discharge Regime Investigation - Conclusion

The above investigation showed the glow discharge to produce a regeneration rate 6 - 10 times greater than that of the corona discharge when operating with the same power supply input voltage. Alongside this the glow discharge was 4 times more efficient at using the energy within the discharge to oxidise the PM.
The glow discharge operating power did not appear to affect regeneration efficiency. However, the regeneration rate was found to increase with increasing discharge power. The usable glow discharge power was limited by the potential thermal damage to the ceramic filter structure. The maximum regeneration rate achievable under quiescent conditions without causing damage to filter was found to be 0.66 g.hr⁻¹, requiring approximately 15 W of discharge power, equating to a regeneration efficiency of 39 - 40 g.kW⁻¹.hr⁻¹ with the flyback power supply and external pin electrode configuration used.

Further investigation of the effects on the discharge generation, the regeneration rate and efficiency under simulated exhaust flow conditions is now detailed in the following sections of this chapter.

5.3 Autoselective Discharge Alternating Frequency Investigation

The glow discharge achieved the largest regeneration rate of the high frequency discharges investigated. The previous investigation also showed that the PM oxidation rate was proportional to the glow discharge power. However, the influence of the alternating voltage frequency on the regeneration rate and efficiency required investigation.

Preliminary feasibility research (Harry et al, 1999) included a coarse frequency sweep from 450 kHz down to 20 kHz. The results indicated that there was no performance advantage in operating the discharge outside of the relatively low frequency (i.e. 20 kHz) band. This relatively low frequency enables the use of low cost and durable power supplies developed for television and cathode ray tube screen applications. Therefore, the research detailed in the following sections was aimed at identifying trends and the potential for system optimisation within the frequency range from 10 kHz to 80 kHz. Stable alternating voltage discharges can only be achieved above
1 kHz (Meek and Craggs, 1978). Below 1 kHz, discharges exhibit non-continuous characteristics and they begin to approximate a series of independent discharges. This would stop the continuous cycle of power transfer that was believed to be of benefit in the operation of the Autoselective system in the glow discharge regime.

5.3.1 Discharge Frequency Sweep Experimental Configuration

The investigation required the variation of the supply voltage frequency. The flyback transformer and drive circuit used for the discharge type investigation could only provide an alternating voltage at 20 kHz. The frequency variation was achieved using a signal generator to provide the sinusoidal base signal at the frequency under test. This was then amplified using an AR700A1 700 W power amplifier with a minimum frequency of 10 kHz. The voltage was then stepped-up using a high frequency transformer matched to the frequency under test. If the transformer response function is not matched to the operating frequency then the secondary or output voltage is generally not sufficient to initiate electrical breakdown using the Autoselective electrode configuration. A correctly specified transformer to the frequency under investigation minimises the size and cost of the equipment required. The experimental power supply was described in greater detail previously in Chapter 4, Section 4.4.

Glow discharges of approximately 15 W average power were generated at each frequency under investigation, using a pin electrode positioned 5 ± 0.5 mm from a filter test section in stationary, ambient air conditions. The 15 W discharges at 20 kHz did not cause damage to the filter test sections during the discharge type investigation discussed previously in this chapter. The input power to the overall system varied between test frequencies due to differences in the efficiency of the transformers and driver circuitry. Therefore, the overall system input power did not provide significant insight into operation or effectiveness at this stage of research and system development. The input voltage to the transformers, controlled using the gain on the amplifier, was not equal for all tests. Each transformer had a different
winding turns ratio and a different characteristic efficiency, thus the required primary or input voltage to generate the output voltage and discharge power at the frequency under test was different. The discharge voltage values of all tests were within 6% and the glow discharge average powers across different frequencies were within 4% of the highest value. Each frequency was tested three times using a randomised matrix to prevent spurious time-based effects being introduced into the data.

All regeneration rate measurements for the individual frequencies tested were within 6% of the maximum values. Thus the tests showed adequate repeatability to provide confidence in the data.

### 5.3.2 Discharge Frequency Sweep Experimental Results

The average regeneration rate and discharge power regeneration efficiency results for the frequency investigation are shown in Table 5-2. The regeneration rates achieved using glow discharges of equal power but varying frequency are shown in Figure 5-7. The regeneration rate shows no varying trend as the discharge frequency was varied from 10 kHz to 80 kHz. Since the discharge powers were equal and the regeneration rates achieved by the discharges showed no change, the glow discharge regeneration efficiency did not change with discharge frequency between 10 and 80 kHz.

<table>
<thead>
<tr>
<th>Discharge Frequency</th>
<th>Average Power</th>
<th>Average Regeneration Rate</th>
<th>Average Regeneration Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>kHz</td>
<td>W</td>
<td>g.hr⁻¹</td>
<td>g.kW⁻¹.hr⁻¹</td>
</tr>
<tr>
<td>10</td>
<td>15.2</td>
<td>0.58</td>
<td>38.16</td>
</tr>
<tr>
<td>20</td>
<td>14.9</td>
<td>0.57</td>
<td>38.26</td>
</tr>
<tr>
<td>40</td>
<td>16</td>
<td>0.61</td>
<td>38.13</td>
</tr>
<tr>
<td>80</td>
<td>15.5</td>
<td>0.59</td>
<td>38.06</td>
</tr>
</tbody>
</table>

Table 5-2 – Average regeneration rate and regeneration efficiency achieved by an Autoselective glow discharge operating with a pin electrode in stationary air conditions under various supply voltage frequencies
Figure 5-7 – Regeneration rate achieved using Autoselective glow discharges of equal power (15-16 W, 7 kV pk-pk) at various operating frequencies (pin electrode to PM gap 15 mm)

Previous investigations demonstrated that the filter structure suffered thermal damage when the glow discharge power was increased above 20 W under the stationary ambient air conditions using a filter section loaded to 4 g/l. The discharge frequency investigation was extended to assess if the frequency of the discharge affects the discharge power at which the filter structure was damaged. Tests were carried out at 10 kHz and 80 kHz with steadily increasing discharge power for comparison to the previously conducted 20 kHz test. Observation showed the filter structure was heated aggressively, causing it to glow orange and eventually melt at a glow discharge power of approximately 22 W, similar to the power at which damage was observed at 20 kHz. Thus the thermal damage and fusing of the filter ceramic was not affected primarily by the discharge frequency, but was caused when the discharge power increased above 20-21 W under static quiescent ambient air conditions.
5.3.3 Discharge Frequency Affects Analysis

The Autoselective system regeneration rate had been shown previously to be dependent upon the glow discharge power. As the discharge power increased the mass of PM oxidised per unit time increased. However, the operational frequency of the discharge did not appear to affect the manner in which the power was delivered to the PM and thus the regeneration rate within the frequency range investigated.

The frequency of operation is likely to impact the design of a production power supply for the Autoselective system. The impedances within an electrical circuit excited by an alternating source can be dependent upon the frequency of excitation if they contain capacitive or inductive elements. For example the impedance of a capacitive element within a sinusoidal excited circuit is inversely proportional to the frequency of excitation. Equally importantly, the frequency of operation can influence the design characteristics and size of the transformer, the insulation required to prevent stray electrical breakdown within the electrical components of the power supply and also determine the electrical losses caused by conductor skin effects. As discussed previously, certain high voltage alternating frequencies are commonly used in applications such as televisions and computer monitors; thus robust and inexpensive components for operation at such frequencies have been already developed and hence could be adopted in this application.

5.3.4 Discharge Frequency Affects Conclusions

The frequency of a glow discharge produced in stationary air under quiescent conditions did not affect the PM oxidation rate between 10 kHz and 80 kHz. The regeneration rate achieved by the Autoselective system was not affected by the discharge frequency within the frequency range identified to offer optimal potential for practical and commercially attractive power supply development. The discharge frequency did not affect the power at which the filter structure was thermally
damaged by the glow discharge, indicating the 'temperature' of discharge was not affected by the operating frequency.

The subsequent research to investigate discharge behaviour under exhaust gas conditions used a 20 kHz operational frequency due to the availability of suitable, highly developed, high voltage transformers and circuitry of this nominal frequency.

5.4 PM Oxidation Mechanisms

There were a number of possible mechanisms that the electrical discharges and plasma generated by the Autoselective system may have caused filter regeneration. The discharges were believed to cause PM oxidation, however, investigation was required to confirm the discharge was not merely fragmenting the PM or dislodging it from the wall flow filter. A simple experiment was conducted in which a section of heavily loaded wall flow filter was subjected to an Autoselective discharge orientated vertically, in ambient quiescent air. Positioned approximately 30 mm below the filter section was a white tile covered in a thin layer of epoxy adhesive (see Figure 5-8). If the discharge were to merely fragment or dislodge the PM then it would fall onto the adhesive tile and be evident during examination after the test.

![Diagram showing experimental setup](image)

**Figure 5-8 - Investigation of PM fragmentation and dislodgement from the wall flow filter.**
Following approximately 8 minutes of discharge operation and consequent regeneration of the filter test section, the tile was removed and examined using a microscope. No evidence of dislodged PM was found in the adhesive on the tile. The discharge generated using the pin electrode appeared to be oxidising the PM on the filter and produce gaseous by-products. Further investigation of the regeneration process using a mass spectrometer showed that oxidation was occurring and that the by-products consisted mainly of carbon dioxide (CO₂). These investigations are discussed in detail in Chapter 7, Section 7.1. The following parts of this section discuss the various mechanisms by which the Autoselective discharge could oxidise PM.

Different discharge types were likely to work though different mechanisms, allowing explanation of some of the regeneration characteristics observed with the various discharges described earlier in this chapter.

Three primary mechanisms exist that may account for the oxidation of PM using the Autoselective discharge:

1. plasma generated highly reactive species and radicals within the exhaust flow, which readily oxidise the PM;
2. PM acts as resistor in the discharge electrical circuit, the electric current causing Ohmic heating and raising the PM temperature to the ignition point;
3. high energy density or 'hot' root region of the discharge causes localised heating, raising the PM to the ignition temperature.

The following sections discuss these mechanisms further, along with their likely influence on the oxidation characteristics observed.
5.4.1 Generation of Reactive Species

Electrical discharge plasma is a highly energetic mixture containing accelerated electrons and ions that are capable of causing chemical changes in the background gas and generating chemical species. Such plasma chemistry processes are used widely in purification systems for air and water where electrical discharges generate species such as ozone, as discussed in Chapter 3.

The treatment of gaseous combustion products through the generation of oxidative chemical species is widely reported in published literature. Dielectric Barrier Discharges (DBD) are used in a number of systems for the treatment of engine-out NOx emissions (Hoard et al, 1999, Abrams et al, 1997, Park et al, 1998). Other discharge systems have been developed to generate NO2 from NO, which is then used to cause PM oxidation at ignition temperatures below 550 °C (Matsui et al, 2003, Yamamoto et al, 2003, Kelly et al, 2003).

Generally, the particulate filter regeneration systems discussed in literature require a relatively large electrical energy density (J.m⁻³)(i.e. electrical power divided by the exhaust gas volumetric flowrate) compared to other active regeneration system concepts (Abrams et al, 1997, Penetrante et al, 1997). The plasma systems attempt to generate sufficient reactive species within the gas stream to oxidise the filtered PM rather than operating to directly oxidise PM. Highly reactive species are generally very short lived, due to their reactive nature (Kelly et al, 2003), which significantly reduces the chance of reaction with PM. Thus an effective system relying on this mechanism of oxidation requires either large quantities of oxidative species to be generated or the species need to be generated in close proximity to the PM. Increasing the energy of the electrical discharge increases the number of reacting species within the plasma. If large quantities of reacting species are required then the energy supplied to the discharge must increase. Generating the discharge in close proximity to the PM can also be difficult within standard wall flow filters because of the limitations on electrode shape and configuration. Many particulate filtration systems regenerated by plasma have been developed around new filter components.
such as metallic foams, which act as one of the electrodes within the system. The plasma is then generated within the filter itself, ensuring maximum exposure and contact between the PM and the discharge generated chemical species. The space velocity within these filter systems is relatively limited to minimise losses through diffusion and dissipation of the chemical species before they can oxidise the PM.

This generation of reactive species is likely to be the mechanism responsible for the oxidation of PM observed when the Autoselective system generates a DBD in similar manner to that described in published research (Matsui et al, 2003). The DBD discharge during the discharge type investigation was only in contact with one surface of the PM on the ceramic filter test section. The lack of close contact between the plasma and much of the PM minimised the regeneration rate possible using the DBD generated by the Autoselective system.

5.4.2 Ohmic Heating

When a potential difference is applied to a conductive material, the electric field causes 'free' electrons to take up a drift velocity ($\sim 10^{-3}$ m.s$^{-1}$) towards the point of higher potential. This net flow of charge constitutes the electric current.

As the electrons move through the conductor they collide with the material microstructure. The electrical resistance of the material is due to these collisions. The kinetic energy gained by the electron during acceleration under the electric field is transferred to the microstructure. This increases the vibration energy of the microstructure and so increases the temperature. This heating effect caused by electric currents is known as Ohmic heating. Ohmic heating is used in a number of applications including domestic water heating and lighting.

The heating effect is enhanced when the applied voltage is alternating. The alternating currents generate magnetic fields within the conducting material. These magnetic fields interact with the current carrying electrons and force them towards
the surface of the conductor producing a skin effect. The higher the alternating frequency the closer the electrons are forced towards the conductor surface, thus the smaller the area through which the current actually flows. The resistance (R) of a conductor of cross sectional area (A), length (L) and material bulk conductivity (\(\sigma\)) is given by Equation 8.

\[
R = \frac{L}{A\sigma}
\]

Equation 8

Therefore, as the frequency increases and the effective conducting area (A) through which the current flows reduces and the apparent resistance increases. The increase in resistance leads to an increased heating effect for a given current under alternating conditions.

The electric current delivered by the discharge to the PM could cause a heating effect to the extent where the PM reaches its ignition point and oxidises rapidly.

Ohmic heating is caused throughout the current carrying regions of a conductor. However, observation of the Autoselective glow discharge clearly showed regeneration occurred only at the discharge root. Only the region of PM at the discharge root is heated and oxidised. No region distant from the root is obviously heated, thus the bulk material resistance is unlikely to cause the ignition of the PM. In addition to this, the large surface area of the PM would result in rapid convective losses of any heat generated through purely Ohmic effects.

Alongside this, the skin effect should result in high frequency discharges increasing levels of regeneration if the conduction of electricity through PM is a significant mechanism. However, the study discussed earlier in this chapter did not show any affect of changing the frequency of the discharge. As the frequency was increased from 10 kHz to 80 kHz, the regeneration rate achieved remained constant.
5.4.3 Discharge Root Heating

The current carried by the discharge is transferred through the small root region of the discharge by electrons accelerated by the electric fields between the electrode and PM. The collision of these energetic electrons with the PM is likely to produce a heating effect in a similar fashion to the conventional Ohmic heating described above. The heating phenomenon produced by discharges is used in a number of other applications including arc welding and plasma cutting processes. The glow discharge root is essentially a high-density region of highly energetic electrons. The energy from these particles is transferred to the work piece electrode, in the Autoselective system case, the PM, causing significant heating. The rapid and very localised heating effect prevents significant thermal loss and cooling of the PM before ignition and oxidation is complete. It was believed to be this very localised and direct heating of the PM that allowed the Autoselective discharge to cause rapid PM oxidation with relatively low power consumption compared to other regeneration concepts.

5.4.4 Consequences of Discharge Root Heating Oxidation Mechanism

An electrical power supply, such as that used as the source for the Autoselective system, has a characteristic load line between the open circuit voltage and the short circuit current (see Figure 5-9). Increasing the load line of a power supply increases the open circuit voltage and the short circuit current if the ratings of the surrounding components can support the higher load conditions. Such an increase in load was achieved by increasing the voltage supplied to the flyback driver circuit or when using the alternative experimental arrangement discussed, by increasing the gain of the power amplifier.
Comparing this with a typical discharge current and voltage characteristic (as shown previously in Figure 3-4), shows that as the load line is increased the discharge power within a particular regime increases, or, eventually the discharge shifts regime to supply the largest current at the lowest voltage.

Concentrating on the normal glow regime, as the load line increases the discharge current increases whilst the discharge voltage remains approximately constant. The increased discharge current is made up off an increased number of electrons within the discharge root. Increasing the number of electrons passing through the discharge root per second increases the energy transferred to the root region per unit time. This reduced the time taken for the discharge to oxidise the PM at the root, thus leading to an increase in the regeneration rate achievable by the discharge. This explains the effects observed in the discharge selection investigation; as the glow discharge power was increased, the measured regeneration rate increased.

5.5 **Initial Observations of the Autoselective Discharge in Exhaust Like Flows**

Initial experiments were conducted in the hot flow rig to allow observation and qualitative assessment of the glow discharge behaviour under exhaust-like flows. The tests were performed to establish if a stable glow discharge could be generated.
and sustained and whether the discharge was capable of PM oxidation under flow conditions.

5.5.1 Affects of Axial Gas Flow

Figure 5-10 (a) and (b) show photographs of discharges in the hot flow rig in static air and under gas flow respectively. With no gas flow, a single bright discharge was generated between the HV electrode and filter where the PM was oxidised. The discharge was stationary for one to three seconds before moving randomly to a new location on the circumference of the growing regenerated region.

When a gas flow was introduced, the discharge was forced to move rapidly in a circular region around the electrode axis (see Figure 5-10 (b)). Motion of the background gas within the discharge region appeared to beneficially aid the regeneration process in terms of potential area coverage. However, regeneration rate under flow conditions appeared in this brief investigation to be affected detrimentally. The phenomena were investigated further and are discussed later in this chapter.

Figure 5-10 - Photographs of glow discharges within the hot flow rig, (a) in static air; and (b) with a gas flowrate of 4000 l.min⁻¹
The measured discharge voltage and current waveforms were also changed during operation under flow conditions. The glow discharge current contained a number of short-lived filamentary elements every cycle when a gas flow was imposed on the discharge region (see Figure 5-11). The average discharge power was reduced under flow conditions; from approximately 12 W to 10 W in the case of the discharges shown in Figure 5-10 (a) and (b) above.

![Figure 5-11 - Glow discharge current waveforms under stationary and gas flow conditions generated with a pin electrode configuration](image)

**5.5.2 Affects of Heated, Axial Gas Flow**

When the air was heated to a temperature of 400 °C and with a corrected flowrate of 4000 l.min⁻¹, the measured voltage and current waveforms were changed again. The discharges developed fewer filamentary elements in the hot gas flow compared to the ambient temperature airflow. The discharge peak current, neglecting the filamentary elements, increased by 10-15%. The phase difference between the voltage and current was slightly decreased (2-4°) by the effect of hot gas flow, implying the discharge was developing towards the pure glow regime. This should
aid carbon particulate oxidation since a reducing phase difference provides higher average discharge power for equal peak voltage and current supply since the power factor increases towards unity as the phase difference approaches zero. The combination of the increased average current with the reduced phase difference leads to an increase in average discharge power from the 14 W under cold airflow to approximately 16 W under hot airflow.

5.5.3 Summary of Observations of the Glow Discharge In Gas Flow Conditions

The axial gas flow caused the relatively stationary discharge to move rapidly around the axis of the electrode covering a larger area of the filter but appearing to be less effective in regenerating the filter. The apparent reduction in regeneration rate may have been due to the reduced residence time of the discharge at each ground position or the reduced discharge power under discharge flow condition. The discharge current contained filamentary elements within the normal glow discharge alternating current. The effect of these filamentary elements within the discharge current did not produce any obvious effects in discharge appearance or apparent behaviour.

Increasing the gas temperature in the hot flow rig caused the discharge to become less capacitive. The decreasing phase difference between the discharge voltage and current should be beneficial for carbon particulate oxidation because the discharge becomes closer to the pure glow regime, leading to an increase in discharge power compared lower temperature flow conditions.

The following sections now discuss a more detailed and structured investigation to quantify the affects of the key exhaust gas characteristics on the average discharge power and regeneration rate achieved by the Autoselective glow discharge produced using a simple pin electrode configuration. The investigation used the Design of Experiments (DoE) technique to build an efficient matrix of experiments to
provide the required data and then develop empirical mathematical models of the responses to changes in the gas characteristics under test.

5.6  **Basic Pin Electrode - Design of Experiments Investigation**

Preliminary investigations showed that the glow discharge could be generated in a heated flowing gas stream and this discharge was capable of regenerating regions of a loaded wall flow filter. However, preliminary observations under simulated exhaust gas conditions within the hot flow rig showed that the discharge was substantially affected by the gas flow. The affects of the main gas flow characteristics; flowrate, gas temperature, oxygen concentration and humidity; on the discharge regeneration performance may impose constraints on the final system design.

The investigation aimed to screen the exhaust gas characteristics, temperature, flowrate, oxygen and water vapour concentration, to identify their influence on the glow discharge power and the regeneration rate achieved.

5.6.1  **Design of Experiments (DoE) Methods**

A complete investigation of the four major exhaust gas characteristics, where each factor was tested at three levels to identify curvature within the response, would require a minimum of 81 separate experiments ($3^4 = 81$) if a traditional experimental procedure was used. Further, the experimental data would still not be complete for a full analysis. Verification of the experimental procedure and data obtained would be required through the use of replicate points as discussed in Chapter 4.

Alongside the excessive time requirement, a traditional experimental approach would not provide information showing how the factors under investigation interact with each other to affect the responses. Thus the total time to perform this investigation, using a standard experimental technique where each variable was
systematically changed, was considered unacceptable and of limited value. Therefore, Design of Experiments techniques (discussed in Chapter 4) were used to reduce the time required to gather sufficient data to map the response surfaces and also provide information concerning interactions between the experimental factors under investigation. A D-Optimal experimental design, capable of providing data for a quadratic response surface model, was created using the Stat Ease v6.0.10 program. Such D-Optimal designs provide highly efficient experimental matrices in terms of the number of runs they require, offer flexibility in the position of the runs within the design space and can test the extreme values of experimental factors.

The D-Optimal experimental matrix developed using the StatEase Design Expert v6.0.10 software for this investigation is shown in Table 5-3.
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<th>K</th>
<th>Gas Flowrate l.min⁻¹ (STP)</th>
<th>O₂ % Vol</th>
<th>Water Vapour % Vol</th>
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Table 5-3 – D-Optimal experimental matrix for pin electrode exhaust gas characteristics investigation

The experimental matrix shown in Table 5-3 above is sorted into run order, rather than the standard order in which it was initially generated. This randomised run order allows identification of outside factors or time based trends, not included in the investigation, that could influence the response.

5.6.2 DoE Experimental Procedure
Chapter 5 - Autoselective Discharge Fundamental Characteristics Investigation

The experimental procedure used for this investigation was discussed in Chapter 4, but a summary is provided here for completeness.

Cordierite wall flow filters were loaded in the exhaust of a Perkins 1100 series diesel engine. The filters were then sectioned axially into 50 mm x 50 mm test pieces. These small sections of loaded filter allowed the pre regeneration and post regeneration mass to be measured using a high-resolution analytical balance. The mass was measured at a set temperature, after an initial heating period to remove condensed elements from the filter. The test section was loaded into the hot flow rig using the wall flow filter test section support detailed in Chapter 4. This support structure ensured conditions for regeneration of the small test section were as close to those of a similar section within a complete filter. The test section was then regenerated under the stable conditions prescribed within the experimental matrix (see Table 5-3) for a set period. The pre and post regeneration masses were used to calculate the regeneration rate achieved by the Autoselective glow discharge generated by a basic pin electrode configuration within given gas conditions.

During regeneration the discharge current and voltage traces were recorded on a digital oscilloscope. The discharge average power was then calculated as the current and voltage product over 10 seconds of operation. This average power was logged to allow assessment of how the gas conditions effect discharge power and provide a measure of the energy efficiency with which the PM is oxidised.

5.6.3 Pin Electrode DoE Investigation – Experimental Results

The discharge power and regeneration rate results measured during the DoE investigation are shown in Table 5-4 against the run number. The data was entered into the Stat Ease Design Expert software for statistical analysis and model generation.
<table>
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<th>Std</th>
<th>Run</th>
<th>Gas Temp</th>
<th>Gas Flowrate</th>
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Table 5-4 - Average discharge power and regeneration rate results from the designed experimental matrix to investigate the effects of simulated exhaust gas conditions on the Autoselective discharge operating with a basic pin electrode configuration. (Shaded runs are replicate experimental points)

5.6.4 Initial Data and Experimental Technique Analysis

The experimental matrix shown in Table 5-4 contains a number of replicate points (shaded runs). As described previously, these replicated runs allowed estimation of variation or measurement error within the experimental technique. Table 5-5 shows
the variation in measured responses at replicate experimental points. The measured regeneration rate varied by a maximum of 5% when the experimental settings are reset and the complete experiment re-run. The measured discharge power varies by approximately 5.5% at these replicate points. The differences in the measured responses at the replicate points was caused by variations in such things as the setting and control of experimental factors as well as variations in the actual measurement of response values.

<table>
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<th>Average Discharge Power</th>
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</table>

Table 5-5 – Pin electrode DoE investigation matrix replicate point analysis

Once the experimental matrix had been conducted, the DoE statistical analysis was then performed. DoE statistical analysis uses Analysis of Variance (ANOVA) techniques in a number of stages as discussed in Chapter 4. The analysis establishes which order model provides the best approximation to the measured data and then calculates a number of statistics indicating how accurate the model is in predicting the measured data. Statistical diagnostics are then used to assess the quality of the experimental design for development of the selected model and provide indications of the quality of the measured data. All of these statistical analysis steps provided a confidence level for the use of the experimental data and developed models in
drawing conclusions of how the response surface was affected by the experimental factors.

The DoE analysis statistics are not detailed here to avoid distraction from the actual analysis of the response surface, discussed in the following sections. However, this should not undermine the importance of the statistical analysis in the use of DoE. The statistics are vital in determining the quality of the data and providing a confidence level for how effective the DoE matrix has been in investigating the experimental space. Therefore, the DoE analysis, model selection and experiment diagnostics for the pin electrode discharge power and regeneration rate responses are detailed in Appendix A1 and Appendix A2 respectively.

5.6.5 Pin Electrode Autoselective Discharge Power Response

The analysis of the DoE investigation data indicated that a linear model could be used to predict the discharge power response. The oxygen concentration and water vapour concentration were statistically insignificant factors in the discharge power response. Only the gas temperature and flowrate were shown to have statistically significant affects on the discharge power response, and were thus included in the model.

The linear model developed through the regression analysis of the pin electrode discharge power experimental data is:

\[ \text{Power}(W) = 15.76 + 3.52 \times 10^{-3} T - 1.81 \times 10^{-4} V \quad \text{Equation 9} \]

where \( T \) = gas temperature (K) and \( V \) = gas flowrate (l.min\(^{-1}@\) STP)

This model was capable of predicting the trends in the discharge power response, however detailed statistical analysis including calculation of correlation coefficients showed that the predicted values did not accurately predict the measured data. The
discharge power measured data against the predicted data is shown in Figure 5-12 and demonstrates the accuracy with which the model can predict the discharge power response for the pin electrode.

![Figure 5-12 - Pin electrode discharge power measured response against predicted response](image)

The linear model can only predict the discharge power experimental data with an accuracy of 6.5%. However, Figure 5-12 shows that the model was capable of indicating the general trends with which the discharge power changes under the influence of the variable under investigation.

The final diagnostics discussed in Appendix A1 showed that the experimental data was reliable and supports the conclusion that the gas flow velocity and the gas temperature were significant factors whilst the water vapour and oxygen concentrations of the gas were statistically insignificant. Variation of the oxygen and water vapour concentrations within ranges experienced in the exhaust gas of a diesel engine do not cause the Autoselective glow discharge power to vary. This was an important finding as it strongly indicated that the Autoselective discharge could be generated under all gas conditions likely to be experienced within a real diesel engine exhaust and therefore was likely to be able to regenerate a filter under all
such conditions. The insignificant factors of exhaust gas oxygen concentration and gas humidity could now be eliminated from future investigation.

5.6.6 Pin Electrode Autoselective Discharge Power Response - Results Discussions

The conclusions that the gas temperature and the flow rate were influential in determining the discharge power when using the pin electrode were supported by the simple inspection of the response graphs shown in Figure 5-13. The response graphs illustrate the measured discharge power at the various levels of the factors tested. The graphs show that the average discharge power decreases as the gas flowrate increases and as gas temperature falls. The average discharge power was not affected by the oxygen and water vapour concentrations within the background gas.
5.6.6.1 Pin Electrode Discharge Power Response to Gas Flowrate

Figure 5-13(a) demonstrates that as the gas flowrate increases the average discharge power decreases. The discharge traces showed common features as the gas flowrate increased. The discharge peak current was observed to reduce as the gas flowrate increases. The charge losses from the discharge region under gas flow result in a reduction in the discharge current. The discharge voltage was also noted to increase as the gas flow increases. Numerous researchers using discharge tubes have reported that as gas flowrate increases the discharge voltage increases (e.g. Raizer, 1997, p 209). The increased voltage was required to increase the ionisation process in
order to develop and maintain a continuous discharge as ionised and ionising particles were removed from the discharge region by the gas flow.

The loss of charge from the current channel in the discharge was due to the entrainment of electrons into the gas flow. This mechanism is commonly known as convective transport (Raizer, 1997, p 209). Such convective, or more accurately termed diffusion losses, occur under quiescent gas conditions but increase substantially under gas flow conditions. The collision frequency of gas molecules with the ionised elements within the plasma is increased by the gas flow through the discharge region. These collisions result in increased losses of ionising particles from the electric fields within the discharge region. This loss of ionising elements from the plasma reduces the current whilst also leading to an increase in the voltage required to sustain a discharge.

The collision frequency between neutral particles and plasma particles in part determines the plasma apparent resistivity (Hippler et al, 2001, p 33). Thus as the flowrate through the discharge region increases the collision frequency, the plasma apparent resistivity increases. Thus a smaller current was produced under high flowrate conditions compared to low flowrate conditions for a given voltage and electrode arrangement.

5.6.6.2 Pin Electrode Discharge Power Response to Gas Temperature

Increasing background gas temperature tends to provide higher power discharges than under low temperature conditions (Figure 5-13(b)). Paschen’s Law states that with a given electrode configuration the breakdown voltage is dependent upon the inter electrode gap and the gas pressure (Meek and Craggs, 1978). However, in many cases the true factor in Paschen’s Law is not the gas pressure, but the number of gas molecules per unit volume, \( N \), or alternatively the gas density, \( p \). This is directly proportional to the gas pressure, and also inversely proportional to the gas temperature. As the gas temperature increases, the gas density reduces. This
reduction in the number of molecules per unit volume reduces the collision frequency within the plasma and thus reduces the plasma resistivity. Thus, generally, under high temperature conditions, higher discharge currents can be generated compared to low temperature gas conditions. The larger currents provide the larger discharge average power that was measured as gas temperature increases.

5.6.6.3 Pin Electrode Discharge Power Response to Gas Oxygen Concentration

Oxygen concentration demonstrates little affect on discharge power (see Figure 5-13(c)). The use of carbon dioxide as a displacement gas showed no measurable affect on the discharge power even though carbon dioxide has a larger dielectric strength than the air that it was displacing (Meeks and Craggs, 1978). The increased carbon dioxide concentrations should therefore lead to an increased voltage that was required to initiate breakdown.

In a mixture of gases the breakdown voltage usually lies between those of the two constituent gases. The breakdown voltage within a discharge gap changes as the gas mixture relative concentrations were altered, but not necessarily in the same proportions (Meek and Craggs, 1978). An increase in breakdown voltage would generally cause a reduction in the current generated by a given discharge voltage and thus a reduction in the Autoselective discharge power.

However, such a change in discharge power was not measured during Autoselective glow discharge operation under simulated exhaust gas streams, consisting of air (oxygen and nitrogen), carbon dioxide (CO$_2$), water vapour and the replenishing nitrogen. The lack of a measurable change in power indicates that the discharge was unaffected by the changes in oxygen and CO$_2$ levels investigated. Further brief tests were conducted under higher concentrations than those likely to be experienced within the diesel engine exhaust. For example, increasing the CO$_2$ levels to approximately 25% of the overall gas flow volume led to a reduction in the discharge power of around 6% compared to quiescent airflow conditions. Increasing
the CO₂ concentration to 35% yielded a reduction in power of approximately 12%. These tests did not provide a thorough investigation of the affects of high carbon dioxide levels (>25%). Maintaining such elevated CO₂ levels was not feasible using the displacement gases in the HFR, and therefore the regeneration performance of the discharge was not measured. However, the tests did confirm that reduced oxygen and elevated CO₂ levels, within the ranges experienced within the diesel engine exhaust, did not significantly affect the discharge power.

5.6.6.4 Pin Electrode Discharge Power Response to Gas Water Vapour Concentration

Figure 5-13(d) shows that elevated water vapour concentration within the simulated exhaust gas, similar to those levels experienced within the diesel engine exhaust, does not produce a statistically significant variation in the average discharge power. Figure 5-13(d) shows that the linear regression analysis does indicate a decreasing trend as the water vapour concentration increases. However, due to the repeatability and accuracy achieved in data collection, the trend could not be distinguished from experimental error or random variation when analysed with a 95% confidence limit.

Numerous researchers have investigated the effects of humidity on electrical discharge generation and behaviour due to its potential impact on industrial plasma processes. Since water has an 'electronegative' characteristic, whereby it can form negative ions through electron attachment, increasing water vapour concentration tends to lead to increased dielectric strength of a gas, as free electrons are removed from the ionisation process (Meek and Craggs, 1978). Increasing the water vapour concentration of air leads to an increase in the breakdown voltage. However, Meek and Craggs (1978) found that the breakdown voltage only increased by approximately 0.2% per g.m⁻³ increase in water vapour concentration when operating with a discharge gap of around 2 cm within a discharge tube; see Figure 5-14. Applying this finding to the Autoselective system operating in simulated exhaust gas conditions should result in a 7-8% increase in the breakdown voltage when operating at 10% water vapour concentration compared to ambient conditions.
However, no increase in breakdown voltage was observed when operating at elevated water vapour concentration. A 7-8% increase in breakdown voltage and the likely reduction in discharge current could easily be measured with the equipment used in Autoselective discharge testing. Therefore, the lack of response was likely to be due to a combination of the factors experienced within the HFR. The water vapour concentration could have interacted with some other variable and thus no longer influenced the discharge behaviour. The relatively high flowrate conditions through the discharge region compared to the environment within a discharge tube may have been minimising the affects of changes to water vapour concentration. The affect of varying the water vapour concentration within the ranges experienced by the diesel engine exhaust was not statistically significant to the Autoselective discharge in this investigation.

Figure 5-14 - Effect of humidity on uniform field breakdown voltage in atmospheric air (Meek and Craggs, 1978, p 545)

5.6.7 Pin Electrode Autoselective Discharge Power Response Analysis

Summary

The affects of the factors investigated by the pin electrode DoE investigation were analysed statistically using ANOVA techniques. The investigation determined that
only the gas temperature and gas flowrate were statistically significant in affecting the Autoselective discharge power. The discharge power was of great interest as previous studies had demonstrated that the regeneration rate achieved by the Autoselective discharge was directly related to the discharge power under quiescent, ambient air conditions. However, further investigation of the Autoselective system’s regeneration characteristics under simulated exhaust gas conditions was required to assess if the oxidation process was influenced directly by the gas flow characteristics as well as the discharge power.

The following sections of this chapter analyse the mass regeneration rate data collected during the pin electrode DoE investigation. In the same manner as described above an appropriate model was selected and the data analysed against this model to establish if any of the investigated factors influence the regeneration rate achieved under the various gas conditions.

5.7 Pin Electrode Autoselective Discharge Regeneration Rate Response

The regeneration rate response required analysis to assess the impact of the gas characteristics on filter regeneration by the Autoselective discharge. An ANOVA analysis, as performed on the discharge power response, was used to assess the quality of the data and experimental process in providing conclusions of how the gas characteristics affect the regeneration rate achieved. The details of the statistical analysis are given in Appendix A2.

The statistical analysis determined that the pin electrode regeneration rate response could be modelled using a two-factor interaction model. The analysis showed that only the gas temperature and gas flowrate had statistically significant affects on the regeneration rate and thus only these terms were included in the model. The analysis also showed that there was an interaction between the gas temperature and gas flowrate factors which in part determined the regeneration rate achieved.
Chapter 5 - Autoselective Discharge Fundamental Characteristics Investigation

The reduced model of the pin electrode regeneration rate was found to be:

\[
(g, \text{hr}^{-1}) = 0.46 + 4.88 \times 10^{-4} T - 3.73 \times 10^{-6} V - 6.60 \times 10^{-8}TV \quad \text{Equation 10}
\]

where \( T = \) gas temperature (K) and \( V = \) gas flowrate (l.min\(^{-1}\) @ STP).

The pin electrode regeneration rate measured values against the values predicted by the model (see Equation 10) are shown in Figure 5-15. The values show a reasonable correlation as estimated by the statistical analysis discussed in Appendix A2.

![Graph showing pin electrode regeneration rate measured values against model predicted values.](image)

**Figure 5-15** – Pin electrode regeneration rate measured values against model predicted values.

The reduced two-factor interaction equation of the pin electrode regeneration rate modelled the actual response data within the design space to an accuracy of 6.5%.

The model and data diagnostics confirmed that the experimental design was adequate to derive the two factor interaction model and that the measured data
points were adequate to support the conclusions demonstrated by the response equation.

The following sections illustrate the variation in regeneration rate response as the experimental factor levels were changed, and then discuss why such response trends are likely to have occurred.

### 5.7.1 Pin Electrode Autoselective Discharge Regeneration Rate Response

The regeneration rate response graphs for each factor investigated are shown in Figure 5-16. The response graphs support the indications from the ANOVA results discussed above. The regeneration rate increases with gas temperature, decreased with gas flowrate and was not affected by the oxygen or water vapour concentration of the gas.
The following discussion assesses the physical meaning of the measured response data for each factor shown in Figure 5-16, and presents possible explanations for the observed trends. Many of the variations observed within the regeneration rate were likely to have been due in some part to changes in the discharge power. The discharge power was affected by the gas conditions within the environment in which it operates as discussed in previous sections of this chapter. The discharge power directly influences the regeneration rate (see Figure 5-17). Thus the gas conditions can affect the regeneration rate through their influence on discharge power as well as directly affecting the oxidation process. The spread of values around the average trend (see Figure 5-17) indicates the oxidation process may be directly influenced by the gas characteristics. Thus the overall change in
regeneration rate with changes in the investigated factors may have been a combination of direct and indirect mechanisms.

![Graph showing regeneration rate response to gas flow rate](image)

**Figure 5-17 – Pin electrode measured discharge power (W) and measured regeneration rate (g.hr⁻¹)**

### 5.7.1.1 Regeneration Rate Response to Gas Flow Rate

Figure 5-16(a) showed that as the gas flowrate increases the regeneration rate achieved by the Autoselective discharge decreases.

The discharge power was previously shown to decrease with increasing gas flowrate due to higher collision losses within the plasma. A reduction in discharge power resulted in reduced regeneration rate. The diminishing number of energetic particles, indicated by the reduced discharge power, reduced the energy transferred to the PM on the filter. Even though the electrons within the plasma are accelerated under a relatively strong electric field due to the higher voltage under high flow conditions, this was not sufficient to counter the affect of the reduced particle number. The reduction in discharge power resulted in less energy being transferred
to the PM at the discharge root, reducing the mass of PM that could be oxidised per unit time. Thus increasing gas flow rate reduced the regeneration rate through its affect in decreasing the discharge power.

The discharge was also vigorously agitated by the introduction of gas flow through the discharge region. The movement was due to the turbulent disturbance of the ionised particles, continuously changing the path of lowest impedance. This caused the discharge to rapidly move between paths and between different ground sites. The reduction in time duration for which the discharge remained at each PM ground site reduced the energy transferred to that individual site. The discharge did not remain at every ground site for sufficient time to always cause complete oxidation of the PM available. As the flow rate increased, the time for which the discharge remained at each site reduced, thus reducing the oxidation caused by the discharge.

Thus increasing the gas flow rate through the discharge region reduced the discharge power, which then resulted in reduced regeneration rate. This less powerful discharge was also vigorously disturbed by the high gas flow rate, reducing the amount of time for which the discharge remained at each ground site and consequently reduced the amount of oxidation caused at each site.

5.7.1.2 **Regeneration Rate Response to Gas Temperature**

Figure 5-16(b) demonstrated that as the gas temperature increased the PM mass oxidation rate increased.

Previous analysis of the discharge power response to changes in gas temperature showed that as the gas temperature increased the discharge power increased. The electrical breakdown voltage and the plasma resistivity reduce under high temperature conditions. These effects lead to high current and consequently high power Autoselective discharges. The high power plasma contains relatively large numbers of energetic particles, which lead to high energy transfer levels through the
discharge root region and increased PM oxidation rates compared to the low gas temperature conditions.

Alongside the increased heating effect produced by the high discharge current, the actual temperature of the PM was elevated under high gas temperature conditions. The high temperature background gas raises the PM temperature. The discharge was then only required to supply the remaining energy to raise the PM to the ignition temperature of 550 °C. As such the plasma may be able to initiate the oxidation of a larger mass of PM per unit time under high temperature conditions than when the PM temperature was not elevated by the background gas. Therefore, the energy required from the discharge to cause oxidation was reduced whilst the high temperature environment in which the plasma operates produces a relatively high power discharge. Combining these effects leads to an increased PM oxidation rate under high temperature conditions.

5.7.1.3 Regeneration Rate Response to the Interaction Between Gas Flow Rate and Gas Temperature

The ANOVA regression model discussed above indicated that an interaction between the gas temperature and gas flowrate factors exists for the oxidation rate response. The interaction is illustrated in Figure 5-18. The oxidation rate was known to increase with increasing gas temperature. However, under high gas flow rate conditions the gas temperature has less of an effect on the oxidation rate compared to low gas flowrate conditions. The gas flowrate determines how the gas temperature influences the oxidation rate.
Observation of the discharge operation showed that the disturbance caused by high gas flow rates reduces the time for which the discharge grounds at each PM site. The reduced time period at each ground site limits the energy transferred to the PM to cause oxidation. As the gas temperature increases the discharge power increases, however, under high flowrate conditions the effect of the increased plasma energy was limited since the discharge does not remain at each ground site for sufficient time to cause oxidation. The gas flowrate determines the duration of time the discharge remains at each ground site, and thus limits the effect that increasing the gas temperature can have on the oxidation rate, producing the interaction observed in Figure 5-18.

5.7.1.4 Regeneration Rate Response to Gas Oxygen Concentration

Figure 5-16(c) demonstrates that variations in the oxygen concentration similar to those experienced within the diesel engine exhaust gas have no effect on the oxidation rate achieved by the Autoselective discharge.
Previous analysis showed that the discharge power was not affected by the oxygen concentration in the range under investigation. However, the oxygen concentration may be expected to affect the oxidation process. Reducing the oxygen concentration could limit the oxidation rate, in a similar manner to a flame being quenched in an airtight container. Figure 5-16(c) does not show such an effect.

The average oxidation rate achieved by a single Autoselective discharge from a pin electrode was approximately 0.6 g hr\(^{-1}\). Assuming the oxidation process produces only \(\text{CO}_2\) in the reaction shown in Equation 11, only 1.6 g of oxygen was required per hour to support the regeneration produced by a single electrode.

\[
\text{C + O}_2 \rightarrow \text{CO}_2 \quad \text{Equation 11}
\]

Under the relatively low flow rate of 1600 l.min\(^{-1}\), with a 2\% oxygen concentration at 200 °C, the gas flow supplies a total of 1578 g of oxygen per hour. Considering an average discharge regeneration site with a 20 mm diameter, 32 g of oxygen will pass through the regeneration region every hour, which was 18 times greater than the amount required to support the oxidation rate produced by the discharge.

Considering a 5.66” (144 mm) diameter filter with an average loading rate of 5.5 g.hr\(^{-1}\) (Information provided by Caterpillar Inc, 2004), 14.7 g of oxygen would be required every hour to support continuous regeneration. A 2\% oxygen concentration gas flow at a relatively low flow rate provides 1578 g of oxygen per hour. The oxygen supply was therefore sufficient to oxidise 590 g of carbon per hour.

Therefore, the lowest oxygen concentrations experienced within the diesel engine exhaust were sufficiently larger than those required to support the continuous regeneration rate achieved by the Autoselective discharge that variations show no affects on the regeneration rate.
5.7.1.5 Regeneration Rate Response to Water Vapour Concentration

Figure 5-16(d) shows that the water vapour concentration of the gas flow has no measurable effect on the regeneration rate. Previous analysis has shown that the water vapour concentration has no significant affect on the discharge power, and thus will have no subsequent influence on the regeneration rate. The water vapour concentration also appears to have no direct affect on the actual oxidation process, and therefore the regeneration rate.

5.7.2 Pin Electrode Autoselective Discharge - Regeneration Rate Response Summary

The regeneration rate data collected during the DoE investigation was analysed using ANOVA techniques, which established that the regeneration rate was affected by the exhaust gas flowrate and temperature. An interaction was also found to exist between the gas flowrate and temperature. The exhaust gas temperature had a larger affect on regeneration rate when the gas flowrate was relatively low. The gas temperature and flowrate were believed to affect the regeneration rate directly through disturbance of the discharge and changes to the background gas characteristics, and also indirectly through their influence on the discharge power.

The data collected during the DoE investigation allowed regression models to be developed for the prediction of the pin electrode Autoselective discharge power and regeneration rate. The accuracy of these models was tested using a number of statistics, however, further validation of the models was conducted using points within the design space that were not tested within the original DoE matrix.
5.7.3 Pin Electrode DoE Investigation – Validation of Developed Models

The final process in a Designed Experimental investigation in which a response surface equation has been produced is the validation of the equation using points within the design space that have not been previously tested.

The discharge power and regeneration rate models produced from the experimental matrix indicate that only the gas temperature and gas flow rate have significant affects on the responses. Therefore, only these significant factors were included within the models and only these factors were varied during the validation tests. The other factors previously investigated, which had been found not to affect the response were positioned at the most convenient condition. The oxygen and water vapour concentrations were not modified from ambient levels during the model validation runs.

A small number of validation runs were conducted to provide some level of confirmation that the models were valid for gas flow rate and gas temperature conditions that had not been previously tested. The gas temperature and gas flow rate conditions selected for the validation runs were the mid points of those tested in the DoE matrix. These conditions are shown on the map of the design space for the gas temperature and gas velocity shown in Figure 5-19.

![Figure 5-19](image)

Figure 5-19 – Gas temperature and gas flowrate design space map showing points included in the DoE experimental candidate list and the validation run points.
The validation tests were conducted using the same experimental procedure as used for full DoE investigation. The analysis comparing the predicted and measured response data from the validation runs is shown in Table 5-6.

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<td>310</td>
<td>0.625</td>
<td>17.18</td>
</tr>
</tbody>
</table>

Table 5-6 - Pin electrode DoE model validation test runs with model predicted and experimentally measured responses

The regeneration rate model predicted the response of the validation runs to within 5% of the measured data, whilst the average discharge power was predicted to within 2%.

Analysing the full DoE matrix, the discharge power predicted values were within 5% of the measured values and the predicted regeneration rate values were within 6% of the actual values. Thus both the regeneration rate and discharge power models can predict the response values to within 5-6% of the actual measured values.

The variance between the predicted and validation run experimental data is graphically illustrated in Figure 5-20. There does not appear to be any pattern within the variation between the predicted and measured values. This indicates that the developed model can only be improved through improvements in experimentation procedure to aid repeatability and response measurement techniques. This improved measurement accuracy should allow the model coefficients to be modified to provide a more accurate model. The variation between the model and predicted values does not appear to be due to some influencing factor that has been omitted in error from the model, rather it was due to random experimentation and measurement error.
Figure 5-20 – Predicted against measured data from pin electrode validation runs.
(a) regeneration rate, (b) discharge power

The validation runs have confirmed the model accuracy. The models developed from the DoE matrix were capable of predicting the response of the pin electrode discharge power and consequent regeneration rate to changes in the gas temperature and flowrate with an accuracy of 5-6%.
5.7.3.1 Pin Electrode Response Surface Model Validation Summary

The Designed Experimental investigation showed that the gas flowrate and the gas temperature influenced the Autoselective discharge power. The oxygen and water vapour concentration of the gas flow showed no affect on the discharge power.

The variations in discharge power contributed to changes in the regeneration rate achieved by the Autoselective discharge. Alongside the regeneration rate changes caused by the variation in the discharge power, the discharge behaviour was altered directly by the gas flowrate and the gas temperature, which was in turn believed to influence the regeneration rate. The oxygen concentration did not affect the oxidation mechanism. The gas flow rates through a typical filter were sufficient to support the oxidation rates initiated, even under the low oxygen concentrations likely to be experienced within the exhaust gases of a highly loaded diesel engine. The water vapour concentration of the gas did not affect the regeneration rate.

The average pin electrode Autoselective discharge power was 17 W. The discharge power increased with gas temperature and reducing gas flowrate, to a maximum of 19 W. The minimum discharge power observed in testing the pin electrode was 15 W.

The average regeneration rate of a single Autoselective discharge from a pin electrode was 0.6 g.hr\(^{-1}\). The minimum regeneration rate measured in testing was 0.5 g.hr\(^{-1}\), measured following operation under low temperature and high gas flowrate conditions. The maximum regeneration rate of 0.74 ghr\(^{-1}\) was achieved under high temperature and low gas flow rate conditions.

These characteristics produce an average regeneration or oxidation efficiency where 36 g of PM is oxidised per hour per kW of discharge power transferred by the plasma.
Chapter 5 - Autoselective Discharge Fundamental Characteristics Investigation

The DoE investigation allowed response surface equations to be developed to model the discharge power and regeneration rates under the gas conditions within the experimental design space. These models were validated within the design space investigated. Comparing the response values predicted by the models to those measured during experimentation showed both models to be accurate to within 5-6% of the measured data.

The investigations discussed thus far have established that the basic Autoselective glow discharge could be generated stably under typical engine exhaust gas conditions and that the discharge caused the oxidation of PM. The following sections of this chapter discuss some of the observations and development work that aimed to allow the Autoselective discharge to be utilised in a prototype regeneration system.

5.8 Pin Electrode Autoselective Discharge – Regeneration Penetration

The preliminary investigations discussed in the preceding sections have demonstrated that glow regime electrical discharges can oxidise PM from a ceramic surface, and in doing so regenerate a diesel filter under exhaust like conditions. However, examination of all test pieces showed that the regenerated volume penetrated to a maximum of 30 mm into the front face of the filter (see Figure 5-21). The remainder of the filter was not regenerated by the electric discharge.
Only the PM at the root of the discharge was oxidised. If the PM was not brought into contact with the discharge root then regeneration did not occur. The length of a discharge gap using a given electrode configuration under given gas conditions in part determines the voltage required to cause electrical breakdown according to Paschen’s Law (Meek and Craggs, 1978). The electric field within the discharge gap can be enhanced by certain geometric features such as shaping the electrodes to a point, which leads to high electric field gradients and a consequent reduction in breakdown voltage. However, even when the shape of the electrodes is optimised, as the pin electrode regenerates the filter, the ground was effectively moved away from the HV electrode as the PM was oxidised.

Consultation with diesel engine and heavy-duty commercial vehicle manufacturers indicated that the acceptable power supply voltage was Practically limited to approximately 30 kV pk-pk (11 kV rms). Such a limit was based partially on the safety of any production device but also minimises the requirement for extensive insulation to prevent electrical breakdown within circuit and transmission components. However, this voltage eventually becomes insufficient to produce an Autoselective glow discharge over the gap from the HV electrode to the PM as regeneration progresses. Therefore, the discharge initially changes regime, reducing the regeneration rate, and may eventually cease, ending the regeneration process. Consequently only the 30 mm of the wall flow filter closest to the pin external electrode was typically regenerated, leaving the majority of the typical 6-inch long filter not regenerated.
Chapter 5 - Autoselective Discharge Fundamental Characteristics Investigation

The Autoselective system therefore required an electrode and filter configuration that allowed the limited length discharge to regenerate the complete filter length whilst operating at practical achievable voltages.

### 5.9 Reduced Length Wall Flow Filter

The filter could be shortened to allow the external pin electrode to regenerate a greater proportion of the filter length. However, using a discharge voltage of 12 kV pk-pk (4.5 kV rms), the maximum discharge length observed under flow conditions was 30 mm. Therefore, to enable an external pin HV electrode positioned at the front face to regenerate the complete filter, the filter could only be approximately 40 mm in length assuming the end plugs were 10 mm long. The effective filtration length of each channel would only be 20 mm (see Figure 5-22).

![Figure 5-22 - Reduced length wall flow filter with single pin HV electrode positioned at the filter front face](image)

An alternative design could have an external pin electrode at both ends of the filter (see Figure 5-23). The filter length could increase to a maximum of 60 mm to enable the complete filter length to be regenerated by two 12 kV pk-pk (4.5 rms) discharges operating from either end of the filter. The effective filtration length is doubled to 40 mm.
Both options of reducing the wall flow filter length lead to a significant increase in the clean filter pressure drop. Using a wall flow filter backpressure model developed by Konstandopoulos et al (1999) the pressure drop for various filter lengths was calculated and are shown in Table 5-7. The reduction in filter length significantly increases the pressure drop across the clean filter, impacting engine fuel economy and performance. Reducing filter size also reduces the amount of PM that can be stored within the filter prior to regeneration being required. The increased regeneration cycles increase the total energy demanded by the system with the consequent fuel efficiency penalty and can also can lead to thermal fatigue of the filter monolith.

<table>
<thead>
<tr>
<th>Wall Flow Filter Length</th>
<th>Calculated Clean Filter Pressure Drop</th>
</tr>
</thead>
<tbody>
<tr>
<td>mm</td>
<td>inches</td>
</tr>
<tr>
<td>152.4</td>
<td>6.00</td>
</tr>
<tr>
<td>60</td>
<td>2.36</td>
</tr>
<tr>
<td>40</td>
<td>1.57</td>
</tr>
</tbody>
</table>

Table 5-7 – Calculated clean filter pressure drop of various 5.66” diameter wall flow filters (2900 l.min⁻¹ at STP)

Thus changing the filter length to allow the external pin electrodes to regenerate the complete filter volume has detrimental effects on filter backpressure, energy demands and filter durability, and thus was not considered as a practical option.


5.10 Ceramic Foam Filter

Ceramic foam filters have been investigated by a number of researchers as an alternative to wall flow filters. A number of researchers including, among others, Zhi and Yongsheng (1999) and Mizrah et al (1989) have discussed the use of ceramic foams to filter PM from diesel exhaust gases. The ceramic foams detailed in the published research have demonstrated lower collection efficiency than wall flow filters for similar clean backpressure. However, the foam filters described in the research are 15 mm (Zhi et al, 2000) to 60 mm (Mizrah et al, 1989) in depth. Therefore, the Autoselective discharge generated using an external pin electrode configuration was capable of regenerating the full length of the ceramic foam filter.

Dynamometer engine tests conducted by Xinyun et al (2000) on Cordierite ceramic foams demonstrated a non-uniform deposition of the particulate along the depth of the filter. Depending upon the pore structure of the ceramic foam and the conditions under which the filter is loaded, the majority of the PM can be trapped in the front portion of the filter, nearest to the pin electrode, aiding regeneration.

A 5.66” (143 mm) diameter Cordierite open pore ceramic foam, 30 mm in length, was loaded in a diesel engine exhaust with a total of 2 g of PM, providing a loading of approximately 4 g.l⁻¹. Tests showed that a pin electrode was capable of causing filter regeneration under simulated exhaust conditions in the hot flow rig (Figure 5-24).
Sectioning the filter along the flow axis showed that the discharge had penetrated into the ceramic foam, causing regeneration within the filter structure (see Figure 5-25). The discharge performance was tested in the hot flow rig to provide an initial assessment of how the axial gas flow affect the regeneration penetration (see Figure 5-25).

Thus the Autoselective discharge, generated using a pin electrode appears capable of regenerating the full depth of a 20 - 30 mm deep Cordierite foam filter under
exhaust-like conditions. However, the collection efficiency of ceramic foams is 60 - 70\% (Mizrah et al, 1989) compared to the 90 - 95\% (Konstandopoulos and Johnson, 1989, Merkel et al, 2001) of wall flow filters. On going research on the microstructure of ceramic foams is improving their filtration efficiency and backpressure characteristics. However, new materials require significant durability testing to ensure they are able to cope with the harsh exhaust environment. Therefore, the current preferred option for many engine manufacturers is likely to be the wall flow filter.

The research within the remainder of this thesis concentrates on the use of the Autoselective discharge with standard Cordierite wall flow filters. This requires the development of an electrode configuration that allows the stable generation of an Autoselective glow discharge that can reach the full filter length. The maximum length of the discharge achievable using practical voltages under simulated exhaust gas conditions was approximately 25 - 30 mm. Inserting the HV and ground electrodes into the wall flow filter channels to form a 3D matrix, allows a 25 - 30 mm discharge to potentially regenerate the full filter length by generating the discharge perpendicular to the gas flow.

5.11 Inserted Electrode Configuration

An inserted electrode configuration involves small diameter pin electrodes being inserted into the channels of the wall flow filter. The HV electrodes were inserted from one end of the filter, whilst the ground electrodes were inserted from the opposite end (see Figure 5-26). Inserting the electrodes from opposite ends of the filter prevents electrical discharge between the HV electrodes and the ground electrodes outside of the filter where no particulate oxidation would be achieved. The configuration also greatly improves the ease of assembly of the electrodes into the filter channels and also allows the ground electrodes to be connected together outside of the filter.
Chapter 5 - Autoselective Discharge Fundamental Characteristics Investigation

The inserted electrode configuration was tested using the hot flow rig to simulate the conditions experienced with the diesel engine exhaust. The tests were conducted on a standard 5.66" diameter, 6" long, 100 cpsi, 0.017" wall thickness NGK Cordierite diesel filter. The filter was pre-loaded in the diesel engine exhaust to 4 g/l. A flyback transformer with 20 kHz driver circuit supplied the electrical discharge. The average discharge power was calculated to be 12 W.

Sectioning the wall flow filter after testing with an inserted high voltage electrode showed that partial regeneration had occurred along the full length of the 6-inch long filter (see Figure 5-27). Thus by inserting HV and ground electrodes into the channels of a wall flow filter, regeneration of the full filter length appears to be achievable by an Autoselective glow discharge generated with a practical, high voltage power supply.

Figure 5-27 - Sectioned wall flow filter demonstrating the regeneration process has occurred along the full length of the 6-inch long wall flow filter
5.12 Summary of Conclusions from Chapter 5

The research detailed in this chapter produced a number of valuable conclusions concerning the operating characteristics of the Autoselective discharge and its performance in regenerating a Cordierite wall flow filter, including:

1. The glow discharge regime was the most energy efficient and productive discharge regime in oxidising PM from the ceramic surface of a wall flow filter under quiescent ambient air and exhaust flow conditions.
2. The operating frequency of the discharge within the range 10 to 100 kHz did not affect glow discharge power or regeneration efficiency, therefore, highly developed and inexpensive 20 kHz high voltage sources could be used to supply the Autoselective discharge.
3. A discharge capable of regenerating a wall flow filter could be produced under all flow rate and temperature conditions likely to be experienced within a diesel engine exhaust system. The gas flow rate and gas temperature affected the glow discharge regeneration performance. Reducing gas flow rate and increasing gas temperature lead to an increase in the regeneration rate and efficiency.
4. The glow discharge, generated using a pin electrode, was not affected by the oxygen or water vapour concentrations of the gas flow, within the ranges likely to be experienced in a diesel engine exhaust.
5. The regenerated region caused by a pin electrode Autoselective discharge was limited in depth to approximately 30 mm. Therefore, filter geometry or electrode configuration developments, such as inserting the electrodes into the filter channels, were required to allow the complete filter volume to be regenerated using the Autoselective glow discharge.

The following chapter details the research conducted to establish how the characteristics of the inserted electrode configuration affect the discharge and its performance in regenerating the filter. These characteristics include the geometry of the inserted electrode configuration, along with the conditions under which the
discharge operates such as gas temperature and filter loading. The development work culminated in the testing of a prototype system on a dynamometer loaded engine, which is discussed in Chapter 7.
Initial investigations discussed in Chapter 5 provided information on the fundamental characteristics of the Autoselective discharge and how exhaust like flows affect the discharge behaviour. Observation of the discharge regeneration performance demonstrated that a system configuration was required that would enable the Autoselective discharge to regenerate the complete volume of the filter. Initial investigations demonstrated that an inserted electrode configuration was capable of regenerating the full length of a 6" (152 mm) long Cordierite wall flow filter.

This chapter discusses the systematic investigation of the inserted electrode configuration to assess how the electrode configuration design characteristics and exhaust gas variables affect system performance.
6.1 Preliminary Observations of the Inserted Electrode Configuration

Initial observation of the Autoselective discharge generated using the inserted electrode configuration in the HFR aimed to provide insight into the operational characteristics of the discharge and identify areas for research that may develop the system's performance. The preliminary inserted electrode studies used a single HV electrode surrounded by four equally spaced ground electrodes, separated by 20 mm from the HV electrode (see Figure 6-1).

A regenerative glow discharge, produced in a freshly loaded filter was characterised by distinct orange plasma that travelled between the HV electrode and the PM within the filter as shown in Figure 6-2.
However, the same power supply and electrode configuration could also produce two other distinct types of discharges depending upon the filter loading near the HV electrode. When the filter was clean, only a small, faint purple corona discharge was visible around the HV electrode. When the filter loading was between $0.5 - 1.8 \text{ g.l}^{-1}$ the system produced a discharge that rapidly and sporadically switched regime, consisting of an alternating current discharge similar to a glow discharge but containing a large number of short duration, high rise time filamentary elements. This mixed discharge appeared as a blue/purple volume around the HV electrode with a radius of up to 6-8 mm (see Figure 6-3). The volume was filled with small, short-lived filaments that were much less bright than the single high current corona filaments observed in a clean filter. The short duration and lack of emitted light meant the individual filamentary discharges were difficult to distinguish. The mixed discharge consumed 6-10 W and the current and voltage traces are shown in Figure 6-4. When filter loading was above $1.8 \text{ g.l}^{-1}$, the power supply produced the required type of glow discharge as shown in Figure 6-2.
Figure 6-3 - Mixed discharge within a lightly loaded Cordierite wall flow filter

Figure 6-4 - Current and voltage waveforms of the blue, mixed type discharge generated using the inserted electrode configuration in a filter with 1 g.l⁻¹ loading, under gas flow conditions in the HFR

Further investigation of the characteristics and differences between the ‘orange’ and ‘blue’ discharges is discussed later in this chapter based on results from examination of their performance in regenerating a diesel filter in the HFR.

Thus the Autoselective system using the 12 kV pk-pk (peak to peak) output, 20 kHz power supply required a minimum particulate loading of 1.8 g.l⁻¹ to generate a high regeneration rate glow discharge within the filter. If the filter loading fell below this level, the power supply was only capable of producing the a glow discharge
interspersed with filamentary current elements similar to those observed with corona discharges.

6.2 Filter Loading Effects on Autoselective Discharge Generation

The affect of filter loading on discharge generation and subsequent regeneration behaviour was investigated further using a signal generator and amplifier power supply circuit. This enabled the power supply voltage to be varied controllably up to a maximum value of approximately 25 kV pk-pk.

At filter loadings above 1.8 g.l⁻¹, the supply voltage could be reduced below 12 kV pk-pk and a glow discharge still generated within the filter. However, a threshold voltage still existed below which the discharge switched from the glow to the corona regime. A minimum voltage was required to initiate a glow discharge within the filter and the voltage required was dependent upon the filter particulate loading as illustrated in Figure 6-5. When the power supply voltage was increased above the minimum required to generate a glow discharge, the discharge current increased, leading to an increase in the discharge power. The voltage required to produce glow discharge reduced as filter loading increased.
Chapter 6 - Autoselective System Development for Wall Flow Filter Regeneration

Figure 6-5 – Minimum voltage required to generate a glow discharge within filter at various particulate loadings with the inserted electrode configuration, 20 mm electrode separation

The following sections now discuss investigations that established how the geometric features of the inserted electrode configuration, such as inserted electrode configuration and spacing, further affect electrical breakdown characteristics and regeneration performance.

6.3 Inserted Electrode Configuration Geometric Characteristics

The inserted electrode configuration has a number of variables that could influence performance characteristics and system design, including:

1. Inserted electrode configuration shape; and
2. HV to ground electrode separation or spacing.

These variables and their affects are discussed in the following sub-sections.
6.3.1 Inserted Electrode Configuration Shape

The inserted ground electrode configuration shape around each high voltage electrode was believed to influence the regeneration distribution or pattern and the voltage required to cause the regenerative glow breakdown. Initial observations had shown that the discharge followed a linear path between the HV and ground electrode. Therefore, increasing the number of ground electrodes was likely to improve the regeneration distribution; however, increasing the number of ground electrodes increased the system complexity and part count, which were important practical system design considerations.

Observation of the discharge behaviour during preliminary inserted electrode testing showed clearly that the discharge travelled in the direction of the ground electrodes, within a 50° to 90° sector. This demonstrated that the number of ground electrodes surrounding the HV electrode would affect the regeneration pattern. If an inadequate number of ground electrodes were used, the discharge would not pass through regions that were not sufficiently aligned between the HV and ground electrodes. These regions would, therefore, remain unregenerated. However, increasing the number of ground electrodes would result in increased system complexity and cost. The optimum number and arrangement of ground electrodes would result in an even distribution of regeneration within the enclosed region whilst minimising the required breakdown voltage to achieve glow discharge.

The observation of discharge concentration towards the ground electrodes, the influence on breakdown voltage and the aim to minimise electrode count lead to the selection of a configuration comprising 6 ground electrodes, in a hexagonal configuration, surrounding a single HV electrode.
6.3.2 HV to Ground Electrode Separation

The HV to ground electrode spacing was anticipated to influence the discharge breakdown voltage as described by Paschen's Law. The breakdown voltage of a given electrode configuration under given gas conditions is a function to the HV to ground electrode separation. As the electrode gap increases, the voltage required to cause electrical breakdown increases. This breakdown voltage is proportional to the discharge operating voltage and current (Kuffel et al, 2001), and thus the discharge power. Therefore, the electrode gap, influences the discharge performance and the power supply requirements. In addition to this, the discharge from a single HV electrode should be able to regenerate the filter volume enclosed by the surrounding ground electrodes at a rate at least equal to the PM loading rate of that enclosed volume of filter. The regeneration rate of a single HV electrode, therefore, imposes an upper limit on the potential electrode spacing. However, if each HV electrode requires an individual power supply then reducing the electrode spacing to regenerate a filter that experiences a relatively high fouling rate will increase the number of power supplies required, the total part count and cost of any production intent device.

6.3.3 Electrode Separation Affects on Breakdown Characteristics

The HV to ground separation of a hexagonal inserted electrode configuration was varied from 10 to 30 mm (see Figure 6-6). All tests were conducted under constant gas conditions within the HFR and used filter sections loaded to 2 g.13.
At each electrode spacing within each filter loading the voltage required to initiate the regenerative glow discharge was measured. Figure 6-7 shows that the voltage required to produce a glow discharge within the filter increased as the electrode spacing was increased. Paschen’s Law describes the breakdown function of a given electrode configuration as a function of the product of gas density and the discharge gap. Increasing the gap across which the Autoselective discharge was generated increased the voltage required to cause electrical breakdown.
Observation of the glow discharge within the filter clearly showed that the discharge rarely passed directly from the HV electrode to the ground electrode. Instead the discharge passed from the HV electrode to a PM ground site between the HV and ground electrodes. During hot flow rig tests on pre-loaded filters, the discharge initially tended to be short, oxidising PM close to the HV electrode. As regeneration progressed the discharge became longer, oxidising PM further from the HV electrode. As such the actual discharge length is not simply a function of HV to ground electrode spacing. The proximity of PM to the HV electrode affects discharge length, but does not appear to affect the voltage required for breakdown. For example, in a pre-loaded filter, the discharge initially regenerated the regions closest to the HV electrode. If the discharge terminated and then restarted, the average breakdown voltage did not change by a measurable amount. The voltage required to create a regenerative discharge was a function of HV to ground electrode separation, but the subsequent discharge length was determined by the proximity of PM to the HV electrode.

Figure 6-7 – Measured approximate breakdown voltage at various electrode separations within loaded wall flow filters
The electrode separation investigation was continued to assess the voltage required to generate glow discharges within filters of various loading using electrode separations of 10, 15, 20 and 30 mm (see Figure 6-8). The voltage requirements for glow discharge generation using the various inserted electrode separations followed similar trends where low filter loadings (1.8 - 2.0 g.l⁻¹) required a higher voltage to generate a glow discharge than higher filter loadings (5 g.l⁻¹). As the filter loading increased the required voltage for glow discharge generation reduced.

![Figure 6-8 - Minimum measured voltage required to generate a glow discharge, in various filter loadings, using different HV to ground electrode separations](image)

The breakdown voltage per unit of electrode spacing (i.e. proportional to the dielectric strength) was calculated from the gradients of the lines of Figure 6-8 and plotted in Figure 6-9. The dielectric strength of an insulating material provides a measure of the maximum electric field strength that it can withstand without electrical breakdown.
Figure 6-9 - Inserted electrode effective electric field strength required to generate a glow discharge within Cordierite wall flow filters at various loadings

Figure 6-9 shows that the inserted electrode configuration dielectric strength varies with filter loading and it was this that determined if the high regeneration rate glow discharge could be generated within the filter. The PM within the filter was believed to act as an electron source between the high voltage and ground electrodes. Carbon is known to have a relatively high electron emission rate compared to many metals and significantly higher than ceramics (Meek and Craggs, 1978, p 655-665), although specific data for Cordierite could not be found. Therefore, the larger the PM loading within the filter, the larger the number of electrons emitted per second within a given electric field.

6.4 HFR Testing of the Electrode Configuration

The inserted electrode configuration was tested using the hot flow rig (HFR) to simulate the conditions experienced with the diesel engine exhaust. The tests were conducted on a standard 5.66” (143 mm) diameter, 6” (152 mm) long, 100 cpsi, 0.4 mm wall thickness NGK Cordierite diesel filter. The filter was pre loaded in the exhaust of the Perkins engine to 4 g. l⁻¹.
The HFR conditions under which the configuration was tested are detailed in Table 6-1.

<table>
<thead>
<tr>
<th>Flow Characteristic</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas flowrate (corrected to 0 °C and 100 kPA)</td>
<td>2000 l.m⁻¹</td>
</tr>
<tr>
<td>Gas temperature</td>
<td>200 °C</td>
</tr>
<tr>
<td>Oxygen volume concentration</td>
<td>Ambient (~ 21%)</td>
</tr>
<tr>
<td>Water vapour concentration</td>
<td>Ambient (~ 11 g.kg⁻¹ of air)</td>
</tr>
</tbody>
</table>

Table 6-1 - Gas conditions under which the inserted electrode configuration was initially tested within the HFR

A flyback transformer with 20 kHz driver circuit supplied the electrical discharge. The supply voltage of the driver circuit was set to 110 V, giving a discharge voltage of 12 kV pk-pk. The average discharge power was 12 W.

The HV electrodes were inserted fully into the inlet channels of the filter. The ground electrodes were fully inserted into the outlet channels, from the rear of the filter, each approximately 20 mm from the central HV electrode.

Once the filter had been regenerated for a 5 minute period it was carefully sectioned to allow assessment of the regeneration penetration and effectiveness. The filter channels surrounding the HV electrode showed distinct regeneration as shown in Figure 6-10. No channel had been completely regenerated to the clean filter state, but PM had been removed along the complete filter length.

Figure 6-10 – Sectioned filter from preliminary inserted electrode testing showing the channel regeneration along the complete length of the filter
Channels neighbouring that containing the HV electrode showed greatest regeneration. However, channels 15 - 20 mm from the HV electrode showed signs of partial regeneration. The regeneration in these more distant channels was sporadic. The points where the discharge had grounded are clearly visible by their ‘spot’ regeneration effect (see Figure 6-11). As would be expected the discharge appeared to regenerate the channels closest to the HV electrode first. Once the amount of PM in these close neighbouring channels had been reduced to some level, the next nearest ground sites are located by the discharge and subsequently regenerated. Figure 6-11 shows the discharge did not completely remove all PM from each channel in turn. Instead the discharge tended to concentrate in the channels closest to the HV electrode but did occasionally jump to more distant channels before all PM had been removed from the channels surrounding the HV electrode. The regeneration patterns agreed with observations of the discharge operation during hot flow rig tests. Initially the discharge was very short as it regenerated the channels next to the HV electrode. After approximately 30 seconds of operation the discharge lengthened to approximately 10 mm. Occasionally, the discharge was longer than 10 mm, and occasionally it was shorter as the Autoselective system selected the path of lowest impedance to ground. This behaviour continued for the duration of the 5 minute test, where the average discharge length grew out from the HV electrode towards the ground electrodes.
Chapter 6 - Autoselective System Development for Wall Flow Filter Regeneration

Figure 6-11 - Close examination of the filter test section following initially inserted electrode testing showed partial or 'spot' regenerated by the discharge up to 15 mm from the HV electrode

When the discharge was observed to ground near the HV electrode during the early periods of the tests, it tended to stay in one position for approximately 8 - 10 seconds. As the discharge grew longer, the time it was stationary at any particular ground site reduced to between 3 and 6 seconds. When the discharge remained at one position for a period greater than 4 or 5 seconds the filter monolith became obviously and aggressively heated and glowed orange.

6.5 **Ceramic Filter Thermal Damage**

Close examination of the sectioned filter showed significant damage had been caused to the ceramic walls during the regeneration process (see Figure 6-12). Holes of diameter between 0.1 and 0.6 mm had been created within the filter walls. Such damage produced a low gas flow resistance path through the filter, which would allow un-filtered exhaust gas to pass into the atmosphere. The holes were concentrated in the channel where the HV electrode was inserted and those...
neighbouring that channel. Some smaller holes and signs of lesser thermal damage could be seen in channels upto 6 mm from the HV electrode.

![Holes within the ceramic filter wall post regeneration](image)

**Figure 6-12 - Filter damage caused during the regeneration process using the basic inserted electrode configuration**

Examination of the holes within the filter walls showed that there were signs of once molten material around their circumference as shown in Figure 6-13. Other areas of the filter wall had a similar glassy or once molten appearance. Again microscopic examination indicated that the ceramic surface had been melted (see Figure 6-14).

![Holes within the filter wall showing a region around the circumference where the ceramic had been melted](image)

**Figure 6-13 - Holes within the filter wall showing a region around the circumference where the ceramic had been melted**
Cordierite has a melting point of 1450 °C (dieselnet.com, 2004). Thus the small melted regions of filter wall had been heated to at least 1450 °C. Cordierite has a low thermal conductivity compared to other filter materials (e.g. Silicon Carbide), which is cited in a number of published works on regeneration systems (Hoj et al, 1995, Gantawar et al, 1997) as the root cause of its susceptibility to thermal damage during filter regeneration. The low thermal conductivity results in the locally heated regions being unable to dissipate the heat energy and thus eventually becoming damaged. Also the highly uneven material temperatures within the filter will result in stressing of the material and eventual fatiguing and possibly cracking of the structure. Three possible mechanisms exist that may have caused this thermal damage:

1. The energy released from the exothermic PM oxidation reaction.
2. The discharge directly heated the region to a temperature above the melting point of the ceramic.
3. A combination of the above mechanisms, where the discharge heats the region and the energy released during particulate matter oxidation increases the temperature above the melting point of the ceramic.

The energy released during oxidation is unlikely to be sufficient to cause the rise in temperature required to cause thermal damage. A number of researchers have
reported thermal damage to particulate filters following rapid regeneration of heavily loaded filters. The filters where damage was observed after Autoselective operation were not heavily loaded. The mass of PM oxidised per unit time by the Autoselective discharge was also relatively low compared to those self sustaining reactions described in published research. The energy released during oxidation of PM by the Autoselective discharge was insufficient to thermally damage the filter ceramic. Therefore, the damage must be caused by some action of the discharge itself.

6.5.1 Cause of Filter Damage

The Autoselective discharge locates the ground site that provided the lowest impedance path to earth. The plasma causes the PM at the ground site to oxidise, as discussed in Chapter 5. The oxidation of the ground site forces the discharge to move to another region of PM. As discussed above, when the discharge was observed to remain in one position for a period of longer than approximately 6 seconds, the filter structure surrounding the discharge root or ground point became obviously heated and glow orange. When the discharge moved between ground sites without remaining at any point for longer than 2 seconds the filter structure did not become visibly heated.

Two possible explanations for the discharge remaining at a particular ground site for an extended period are:

1. A small region of the filter provided a number of closely positioned ground sites that were oxidised in turn. Due to the close proximity of these consecutive sites of oxidation, the exothermic energy released during the reaction or heat released from the discharge raises the filter temperature causing the monolith to become obviously and visibly heated, eventually melting small areas.
2. A 'memory effect' within discharge region of the background gas. An electrical discharge produces ionised particles and causes localised heating within the background gas. Both of these affects can create a region of relatively low impedance. This causes the discharge to remain in that region causing further heating and allowing high gas and root temperatures to develop. When the background gas temperature reaches 700 °C thermionic emission can also begin to contribute to the gas ionisation in the locality (Kuffel et al, 2001). The initial discharge will have oxidised the original ground site. However, the local ionised region and elevated gas temperatures make this original discharge region the new lowest impedance path. The subsequent discharges oxidise PM around the original ground site, elevating the temperature of both the gas and filter monolith. If the process is able to continue for an extended period the filter monolith may become heated above the Cordierite melting point by the energy delivered through the discharge root.

Both of these mechanisms would result in the accumulation of heat within the filter monolith that could lead to the thermal damage observed during testing. Preventing this accumulation of heat and encouraging the discharge to move between ground sites should prevent the thermal damage occurring.

6.6 Discharge Interruption Using an On Off Time Duty Cycle

Switching the discharge off for a short period allowed the retained heat energy and also the ionised particles from the original discharge to dissipate into the gas flow, preventing repeated discharging to the same region and allowing the filter ceramic to cool between discharges. Once the heat energy within the filter monolith was dissipated the discharge could be switched on again. Trials with such a duty cycle or marks-space ratio imposed upon the power supply used the same flyback transformer as used in initial inserted electrode testing, providing 12 kV pk-pk at 20 kHz. During the on periods the power supply provided a discharge of
approximately 11 W average power, the same as previously tested when the filter suffered thermal damage in the HFR.

The initial tests used a duty cycle consisting of a 250 ms on period and 250 ms off period created by a square wave signal generator within the power supply circuit. The Autoselective discharge exhibited significantly more movement when compared to tests using an uninterrupted discharge under the same gas flow conditions. The discharge rarely remained in one position for consecutive on periods. The filter monolith did not become as powerfully heated as in the previous tests, although small sections of the filter did occasionally glow orange. Four tests where conducted at various gas flowrates. The gas flow rate had been previously noted to influence the discharge movement. High gas flow rates caused the discharge to move more vigorously than low flow rates during the preliminary pin electrode testing (discussed previously in Chapter 5). Potentially the larger flow rates may still have caused the discharge to move to a greater extent with the inserted electrode configuration. However, the filter channels had a flow straightening effect, which reduced the influence of increasing gas flow rate on the movement of the discharge generated within the filter by the inserted electrode configuration.

Upon sectioning the test filter the level of thermal damage was found to have reduced from that observed following the continuous discharge testing. The damage was reduced in severity (see Figure 6-15) with fewer complete holes created, however, the number of damage sites and their distribution was similar to that from continuous discharge operation.
The damage observed in Figure 6-15 indicated that excessive localised heating was still being caused to the filter wall. The damage showed that these small areas of filter had been heated above 1450 °C. Such localised heating and melting would reduce the mechanical strength of the filter and the indicate temperature gradients had existed that would induce stresses within the ceramic structure. Since the damage was caused by a single regeneration, the filter would not be expected to survive the thousands of regenerations that it would undergo during service on a vehicle. Within the melted regions, the porous ceramic wall had been fused, preventing these regions from contributing to filtration. Again, since the coverage of the damage shown in Figure 6-15 was from a single regeneration process, the size of the area removed from effective filtration by fusing would soon become significant. The fused pores reduced the filtration area, reducing the amount of PM that the filter can hold prior to regeneration being required. Therefore, even the reduced severity damage shown in Figure 6-15 would be unacceptable. The duty cycle specifications required further investigation to assess if an on and off time combination could be established which would eliminate all filter damage during the regeneration process using the Autoselective discharge.

Whilst the duty cycle reduced the damage caused to the filter structure during regeneration, it also reduced the amount of time the discharge was actually operating. As such it reduced the mass of PM that could be oxidised by a single electrode in a given time. The number of HV electrodes required to oxidise any level
of engine-out PM was therefore increased through the use of the on/off duty cycle. The cost and complexity of a production Autoselective system would consequently be increased. The optimal on and off timing combination would maximise the regeneration rate achieved by a HV electrode whilst preventing damage to the filter material and structure. The following sections discuss the investigations that aimed to optimise the duty cycle.

6.7 Duty Cycle On / Off Time Optimisation

The duty cycle on time was reduced whilst maintaining a constant off time of 150 ms. Each on time period length was tested in different locations within the same filter. The average discharge power during the on period was maintained at a constant level (11-12 W), as were the HFR gas conditions (200 °C, 2800 l.m⁻¹ @ STP, ambient oxygen concentration and humidity).

When the on time period reduced, the severity of the damage continued to decrease, following the trend observed in the preliminary duty cycle testing. Once the on time period fell below 60 ms the filter was found sustain no damage (see Figure 6-16), even under microscopic examination of the ceramic wall (see Figure 6-17). The discharge did not operate in one position for sufficient time to cause the wall flow filter ceramic to melt.
Figure 6-16 - Wall flow filter following regeneration using the Autoselective system with 50 ms on/150 ms off duty cycle to prevent thermal damage using a 11-12 W Autoselective glow discharge

Having established an on time period that did not allow the filter to be damaged, the off time period was systematically reduced to maximise the regeneration rate whilst still ensuring adequate discharge movement within the filter to prevent damage.

The on time period was set to 50 ms and the tests were conducted on a single filter of similar loading to that used during the on time investigation (~ 4 g.l⁻¹) and under constant HFR conditions (200 °C, 2800 l.m⁻¹ @ STP, ambient oxygen concentration
and humidity). The discharge power was set to the same level as in the on time investigation, at 11-12 W.

After testing, the filter was sectioned to assess regeneration effectiveness, patterns and importantly, evidence of thermal damage. The sectioned filter showed signs of thermal damage similar to that shown in Figure 6-15 when the off time had been reduced below 25 - 30 ms.

The discharge was observed to become less mobile within the filter when the off time period was reduced below 25 ms. When this occurred the filter became visibly heated as the discharge remained in the same position for repeated periods of the duty cycle. This reduction in mobility at short off times allowed the filter to become heated above the ceramic melting temperature.

When the filter structure was not damaged, the novel pressure mapping technique developed for local backpressure evaluation (discussed in Chapter 4) was used to assess regeneration effectiveness and distribution. The pressure maps of the individual regeneration regions where no damage was apparent are shown below in Figure 6-18. When the filter structure had been damaged, the small holes within the filter walls would provide relatively very low resistance paths to the gas flow and thus would disguise the affect of filter regeneration, and hence pressure mapping was not used.
Figure 6-18 – Post regeneration pressure maps taken from filter sections without damage, using various duty cycle off time periods

The pressure maps demonstrated that as the off time period reduced, the area regenerated by the discharge, during the fixed period of operation, increased. This was confirmed when the filter was sectioned after pressure mapping.

6.7.1 Gas Flowrate Affects on Duty Cycle On/Off Time

When the off time was maintained at 30 ms or above the discharge movement between consecutive ground sites was sufficient to prevent significant heating of the filter under gas flowing conditions. The rate of heat dissipation was likely to be a function of the gas flowrate through the filter. At low gas flow rates the duration of the off time period should be increased compared to under high flowrate conditions. This allows adequate time for the energy within the hot region of the filter to dissipate. This effect was investigated by regenerating a portion of filter under no flow conditions. The filter section was loaded with PM to a similar level to those used in previous duty cycle investigations to eliminate any filter loading influences.
A 200 °C gas stream was used to initially raise the temperature of the filter monolith within the HFR. The off time period was set to 30 ms.

The discharge was observed to be less mobile than that generated under gas flow conditions. The discharge often grounded in the same position for 6-8 periods of the duty cycle. The lack of mobility and subsequent filter ceramic heating was similar to that observed when filter damage had been caused and prompted further testing with longer off time periods in an attempt to increase discharge mobility. Tests were conducted at off time periods of 40, 45 ms and 50 ms. The on time period remained at 50 ms.

Sectioning of the filter after pressure mapping showed that damage had been caused to the filter during the 30 ms tests. No holes had been created in the filter walls, but small areas of once molten ceramic could be observed under close examination. The 40 ms test section showed a reduced number of areas of damage compared to the 30 ms section. However, no damage was found when the off time was 45 ms or greater.

As an alternative to the off time period of the duty cycle being increased to 45-50 ms, reduction of the on time may reduce the heating effect of the discharge allowing the off time to remain at 30 ms under quiescent conditions. If the same off time to on time ratio is applied, the on time period should be shortened to approximately 30 ms when the off time is 30 ms. Two regeneration tests were conducted; one with an on time period of 40 ms and one with an on time of 20 ms. Upon filter sectioning the 20 ms on time period showed no sign of damage and the 40 ms region showed initial signs of thermal damage, as expected.

Thus the duty cycle to eliminate filter damage whilst maximising regeneration under all possible flow rates expected within a diesel filter should be periods of a maximum of 55 ms on and a minimum of 45 ms off.
The approximate 1/1 ratio of on to off time periods is known to be applicable to 30 ms on with 30 ms off. The effect on regeneration rate was not actually measured due to time constraints at that point in the research work. However, if the discharge was able input sufficient energy to initiate small local self sustained oxidations at 50 ms on time, there may have been insufficient time to initiate such sustained reactions when the on time was reduced to 30 ms. This would result in a reduced regeneration rate and regeneration efficiency.

### 6.7.2 Affects of Discharge Power on Duty Cycle to Prevent Thermal Damage

Ceramic wall flow filter damage caused by the Autoselective discharge operation was caused by a build up of heat energy within the discharge region. Reducing discharge power may have allowed longer on time periods to be used. This may have been beneficial to the regeneration rate whilst also reducing the maximum power drawn by the power supply.

The amplifier and high frequency transformer circuit experimental power supply (discussed in Chapter 4) was used to provide discharges of various power but constant waveform and frequency. The flyback power supplies were unable to provide varied power discharges in a sufficiently controllable manner. The amplifier and transformer circuit allowed high regeneration efficiency glow discharges to be generated with a range of powers between 8 and 20 W.

Increasing the discharge power from around 8 W to above 20 W increased the regeneration rate achieved by the system in the HFR in a similar manner as observed under preliminary glow discharge investigations (discussed previously in Chapter 5). However, significant filter damage occurred during the high power discharge testing. The severity of the damage increased as the discharge power increased. Increasing discharge power lead to increasing temperatures being developed within the filter. A series of tests on similarly loaded filters under constant flow conditions showed that the on time period needed to be reduced to between 20 and 25 ms for a
20 W discharge in order to prevent thermal damage when the off time was maintained at 50 ms.

Stably reducing discharge power below 8 W was difficult with the power amplifier circuit since the discharge regime tended to change towards becoming a corona discharge.

These initial investigations of the Autoselective system proved that the inserted electrode configuration was capable of regenerating the full filter volume. However, without power modulation, by switching the discharge on and off in a duty cycle, the Autoselective discharge caused thermal damage to the ceramic wall flow filter. The duty cycle was optimised to ensure adequate performance under various gas and filter loading conditions whilst maximising the regeneration rate achieved.

The influences of key design variables of the inserted electrode configuration had therefore been established. The following sections discuss the investigation of how the developed inserted electrode configuration performed in exhaust like flows and quantifies the affects on discharge power and regeneration rate. The investigation followed on from the Design of Experiments (DoE) investigation discussed in Chapter 5, which established how the main characteristics of a diesel engine exhaust gas flow affect the operation of the basic Autoselective glow discharge generated using a pin electrode.

### 6.8 Inserted Electrode Configuration DoE Investigation

The investigations detailed in the previous sections of this chapter have described how the characteristics of the inserted electrode configuration affect the Autoselective system operation and performance. Preliminary investigations also showed that the filter loading influences the Autoselective discharge operation.
Further investigation of the affect of filter loading on the regeneration performance was required.

The inserted electrode configuration significantly changed the conditions within the space where the Autoselective discharge occurred compared to the pin electrode. The majority of the gas flow was now perpendicular to the direction of discharge travel instead of parallel. The affects of the gas characteristics on the regeneration performance achieved by the inserted configuration therefore needed to be established.

The use of the Design of Experiments (DoE) methods for the efficient investigation of system responses to multiple factors was discussed in Chapters 4 and 5. The DoE technique known as Response Surface Methodology was used to investigate the gas characteristics that affect the performance of an Autoselective discharge generated using the inserted electrode configuration. The technique reduces the number of experiments required to provide a statistical analysis and model of the response surface only containing influential factors.

6.8.1 DoE Experimental Procedure

The investigation aimed to determine the discharge power and regeneration responses to the environmental factors gas flow rate, gas temperature and filter loading; under which the inserted electrode configuration would be expected to operate.

The filter loadings under investigation were relatively low. A key characteristic of the Autoselective system was its ability to regenerate a filter from relatively low loading conditions. Preliminary investigations had indicated that the glow discharge could be generated within a filter loading of 1.8 g.l⁻¹ using practically acceptable supply voltages.
The ranges of gas temperature and flow conditions studied were the same as those investigated during the pin electrode investigation. During the pin electrode investigation, the gas oxygen and water vapour concentrations were found not to be influential. Since the gas composition is the same whether an external pin electrode is used or an inserted configuration, these factors were not included in this investigation.

The experimental procedures used in this investigation are detailed in Chapter 4. The power supply utilised for the investigation operated with a duty cycle of 50 ms on, 50 ms off. This prevents the discharge from remaining in one location for an extended period and causing thermal damage to the filter structure. However, the average discharge power recorded in Table 6-2 below is the average power whilst the discharge was operating to allow direct comparison with the pin electrode results. The power was not averaged over a number of on and off periods.

The Design of Experiments software Design Expert was used to determine the D-Optimal experimental matrix required for the investigation. The 18 run D-Optimal matrix required to fully investigate the inserted electrode’s response to the three experimental factors is shown in Table 6-2.
Chapter 6 - Autoselective System Development for Wall Flow Filter Regeneration

Table 6-2 - D-Optimal design matrix for the investigation of the affects of gas characteristics and filter loading conditions on the performance of an Autoselective discharge generated using an inserted electrode configuration

<table>
<thead>
<tr>
<th>Standard Order</th>
<th>Run Order</th>
<th>Gas Flow rate ( \text{L min}^{-1} @ \text{STP} )</th>
<th>Gas Temperature ( ^\circ \text{C} )</th>
<th>Filter Loading g.l(^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>1</td>
<td>2900</td>
<td>240</td>
<td>2</td>
</tr>
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<td>2</td>
<td>1600</td>
<td>400</td>
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<td>4200</td>
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<tr>
<td>11</td>
<td>4</td>
<td>3550</td>
<td>240</td>
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</tr>
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<td>6</td>
<td>5</td>
<td>4200</td>
<td>80</td>
<td>3</td>
</tr>
<tr>
<td>12</td>
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<td>4200</td>
<td>80</td>
<td>2</td>
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<tr>
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<td>7</td>
<td>2900</td>
<td>400</td>
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<td>8</td>
<td>1600</td>
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</tr>
<tr>
<td>2</td>
<td>18</td>
<td>1600</td>
<td>400</td>
<td>2</td>
</tr>
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</table>

The discharge power and regeneration rate results are shown in Table 6-3 against the run number from the design experimental matrix. The power and regeneration rate data was entered into the Stat Ease Design Expert v.6.0.10 software for analysis and model generation.
Table 6-3 - Average discharge power during the duty cycle on period and regeneration rate results from the designed experimental matrix to investigate the Autoselective system with inserted electrode configuration

6.8.2 Initial Data and Experimental Technique Analysis

The experimental matrix shown in Table 6-3 contains a number of replicate points (shaded runs in Table 6-3). As described previously, these replicated runs allow estimation of variation or measurement error within the experimental technique. Table 6-4 shows the variation in measured responses at replicate experimental points. The measured regeneration rate varies by a maximum of 4.5% when the experimental settings are reset and the complete experiment re-run. The measured discharge power varies by approximately 5.5% at these replicate points. The difference in the measured responses at the replicate points was caused by variations in such things as the setting and control of experimental factors as well as variations in the actual measurement of response values.
Once the experimental matrix had been conducted, a DoE statistical analysis was then performed. The analysis establishes which order model provides the best approximation to the measured data and then a number of statistics indicating how accurate the model was in predicting the measured data. Statistical diagnostics were then used to assess the quality of the experimental design for development of the selected model and provide indications of the quality of the measured data. All of these statistical analysis steps provide confidence levels for the use of the experimental data and developed model in the analysis of the actual data, and its use in drawing conclusions of how the response surface was affected by the experimental factors.

The DoE analysis, model selection and experiment diagnostics for the inserted electrode discharge power and regeneration rate responses are detailed in Appendix A3 and Appendix A4.

### 6.9 Discharge Power Response

The statistical analysis of the response data gathered during the Designed Experimental investigation showed that a linear model containing terms for the

<table>
<thead>
<tr>
<th>Standard Order</th>
<th>Run Order</th>
<th>Regeneration Rate</th>
<th>Discharge Power During On Period</th>
<th>Regeneration Rate Difference</th>
<th>Discharge Power Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>16</td>
<td>0.215</td>
<td>10.74</td>
<td>2.4</td>
<td>0.0</td>
</tr>
<tr>
<td>3</td>
<td>17</td>
<td>0.210</td>
<td>10.74</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>9</td>
<td>0.238</td>
<td>10.65</td>
<td>3.0</td>
<td>-5.2</td>
</tr>
<tr>
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<td>18</td>
<td>0.231</td>
<td>11.23</td>
<td></td>
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<td>2</td>
<td>0.286</td>
<td>12.25</td>
<td>-3.4</td>
<td>-3.4</td>
</tr>
<tr>
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<td>8</td>
<td>0.296</td>
<td>12.68</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>3</td>
<td>0.229</td>
<td>11.05</td>
<td>2.0</td>
<td>2.3</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>0.225</td>
<td>10.80</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6-4 - Inserted electrode DoE investigation replicate point analysis
main effects of gas flowrate, gas temperature and filter loading could describe the
discharge power response surface.

The linear model of the inserted electrode discharge power during the on period of
the duty cycle is:

\[
\text{Power} = 9.121 - 2.172 \times 10^{-4} V + 1.612 \times 10^{-3} T + 0.576 L \quad \text{Equation 6-1}
\]

where V = gas flow rate (l.m⁻¹ @ STP), T = gas temperature (K) and L = filter loading
of 100 cpsi wall flow filter (g.l⁻¹).

The response surface equation (see Equation 6-1) provides a means to model the
trends within the inserted electrode discharge power caused by changes to
significant gas characteristics and filter loading. The equation predicts the discharge
power during the on period with a minimum accuracy of 7%. The distribution of the
modelled and measured data is shown in Figure 6-19. The distribution of values
does not indicate any trends within the residuals between the modelled and
measured data. Therefore, the linear response surface model contains all the relevant
terms. The accuracy of the model could only be improved through improving the
accuracy with which the experimental data was gathered and increasing the number
of experimental design points investigated, from which the model was developed.
Figure 6-19 – Inserted electrode on period discharge power measured data against predicted values using the DoE linear model

6.9.1 Discharge Power Data Analysis Summary

The results of the Designed Experimental investigation showed that the power of a discharge generated using an inserted electrode configuration was affected by the gas temperature, the gas flow rate and the filter loading. Analyses (detailed in Appendix A3) including Outlier testing and Cook’s distance calculations showed that the experimental data was reliable and there were no apparent erroneous data points. A regression model of the inserted electrode discharge power was developed from the experimental data. Analysis of the model showed that it fitted the measured response data within the design space to an accuracy of 7%.

6.9.2 Discharge Power Results Discussion

The analysis of the response graphs shown in Figure 6-20 support the conclusions that all the factors investigated here affected the inserted electrode discharge power. These response graphs show the average discharge power measured at the various
levels of each factor investigated. The average discharge power increased with increasing gas temperature and increasing filter loading. Increasing gas flow rate caused a decrease in discharge power. The graphs also indicate that the filter loading is the factor that had the largest affect on the inserted electrode discharge power.
Figure 6-20 - Inserted electrode discharge power response under the tested conditions (a) gas flowrate (b) gas temperature (c) filter loading
6.9.2.1  Affects of Gas Flowrate on Inserted Electrode Discharge Power

Figure 6-20(a) above illustrates that as the gas flow rate increased the inserted electrode discharge power reduced. Similar observations were made when the pin electrode configuration was investigated (Chapter 5). The discharge peak current was observed to fall as the gas flow rate increased. The increased flow rate through the discharge region increased charge losses from the plasma. The ionised particles that make up the plasma collide with the molecules in the gas flow. These collisions lead to energy losses from the plasma particles and some also increased levels of recombination. Overall the number of ionised particles reaching the discharge root fell, resulting in a reduction in the measured current. The discharge voltage required for breakdown increases as the gas flow rate increases; a common result when discharges are generated within a gas stream (Raizer, 1997, p. 209). The increased voltage was required to produce ionised particles at a faster rate than under quiescent gas conditions, to maintain a glow discharge. The increased collision losses within the plasma remove ionised particles. These particles require replacement by increasing the ionisation processes that create the ionised particles that make up the plasma. The discharge power is a function of the product of the discharge voltage and current, however, the increased operating voltage does not fully compensate for the reduced current, thus the measured discharge power reduced under flow conditions. The reduction in power was proportional to the gas flow rate in the range investigated.

The reduction in discharge power is similar to that when using the pin electrode configuration. Increasing the gas flowrate from 1600 l.min\(^{-1}\) @ STP to 4200 l.min\(^{-1}\) @ STP lead to a reduction in the average discharge power of approximately 5\% when using an inserted electrode. When using a pin electrode increasing the flowrate from 1600 to 4200 l.min\(^{-1}\) @ STP produced a 3\% reduction in discharge power.

The smaller change in the discharge power when using the pin electrode configuration at first seemed counter intuitive. The gas flow within the channels of a 5.66” (152 mm) diameter particulate filter, where the inserted electrode generates a
discharge, has a Reynolds Number of approximately 1300. Under the same gas flow rate the Reynolds Number at the filter front face, where the pin electrode discharge is generated, is approximately 18900. These figures ignore the unsteady gas dynamics generated by the gas exchange processes within a reciprocating engine. The lower turbulence levels within the particulate filter channels may result in lower collision losses and disruptions to the discharge resulting the removal of fewer ionised particles. However, since the flow rate had a greater affect on the discharge power under the relatively low Reynold’s Number inserted electrode configuration, the flow turbulence is not the only influential factor.

When using the inserted electrode configuration the gas flow is perpendicular to the direction of the discharge. When using the pin electrode configuration the flow was parallel to the discharge (see Figure 6-21). Effectively the aspect ratio of the discharge present to the flow is larger when using the inserted electrode configuration compared to the pin electrode configuration. This is believed to allow a larger percentage of charged particles to be transported out of the discharge region than occurs when the pin electrode configuration was used. When using the pin electrode, charged particles are transported along the discharge axis. However, the inserted electrode configuration allows a larger number of charged particles to be removed from the discharge region through entrainment into the gas flow. Similar results have been reported in experiments with discharge tubes where longitudinal and transverse electrode configurations have been tested under gas flow conditions (Raizer, 1997, p, 209 & 168). When using the inserted electrode configuration the discharge is not observed to travel down stream towards the rear of the filter following the entrained charged particles. This indicates that the charged particles entrained within the background gas must be dispersed quickly, preventing their numbers building up sufficiently to alter the ionisation characteristics of the gas downstream of a generated discharge.
Alongside the entrainment process charged particles are also removed from the discharge through recombination with background gas molecules. However, this process is likely to cause a larger loss of charge with the pin electrode as the background gas molecules will have a longer residence time within the discharge region compared to the inserted electrode case.

### 6.9.2.2 Affect of Gas Temperature on Inserted Electrode Discharge Power

Figure 6-20(b) shows that as gas temperature increased the discharge power increased, in similar manner as observed with the pin electrode. Increasing the gas temperature from 80 °C to 400 °C resulted in a 4.7% increase in average discharge power during the on period. As the gas temperature increases, the background gas density reduces. The collision frequency between plasma particles and gas molecules reduces with gas density, resulting in a reduction in the effective plasma resistivity. The low plasma resistance allows high discharge currents to be generated, leading to high discharge powers.

The discharge power is influenced to a marginally larger extent when using a pin electrode compared to the inserted electrode. Increasing the gas temperature from 80 °C to 400 °C resulted in a 7% increase in discharge power when using the pin
electrode, compared to 5% with the inserted electrode. The gas density through the regions in which the discharge was actually generated was the same in both electrode configurations, thus the gas temperature could be expected to have the same affect on the discharge power. However, the affect of increasing gas temperature may be expected to be larger when using the inserted electrode configuration than that when using the pin electrode. The inserted electrode generates the discharge in a perpendicular direction to the gas flow. This is believed to make this discharge more susceptible to changes in the gas flow, including the changes in density caused by the gas temperature increasing, than the discharge generated using the pin electrode, which is parallel to the gas flow. This theory is supported by the findings from the flow rate factor investigation discussed above. However, the investigation of the gas temperature did not show this result. The pin electrode discharge, which is parallel to the flow, has a smaller frontal area to length ratio, but appears to be more susceptible to the changes in gas density caused by increasing gas temperature. The cause of the smaller increase in discharge power when using the inserted electrode must lie in some other aspect of how the different electrode configurations produce the discharge or how they allow gas temperature to influence the discharge.

6.9.2.3 Affects of Filter Loading on Inserted Electrode Discharge Power

Figure 6-20(c) demonstrates that as the filter loading increased from 2 g.l\(^{-1}\) to 4 g.l\(^{-1}\) the average discharge power during the on period of the duty cycle increased by 7%.

A previous investigation (Chapter 6, Section 6.2) had shown that as the filter loading increased the voltage required to generate the glow discharge within the filter using the inserted electrode configuration reduced. The overall dielectric strength of the loaded filter system reduced as the PM loading increased. As the filter loading increased the operational voltage reduced but the discharge current increased. The increase in current was greater than the reduction in voltage and this lead to an increase in discharge power as the filter loading increased from 2 to 4 g.l\(^{-1}\). The PM is
believed to act as an electron source between the high voltage and ground electrodes. Carbon is known to have a relatively high electron emission rate compared to some metals and significantly higher than ceramic (Meek and Craggs, 1978, p 655-665). Therefore, the larger the mass of PM within the filter, the larger the number of electrons emitted per second by the carbon. This source of electrons reduces the voltage required for breakdown and also increases the discharge current during operation. The emitted electrons contribute to the ionisation processes during electrical breakdown and sustaining the plasma, resulting in increased discharge currents, and discharge power, as the filter loading increased.

6.9.3 Inserted Electrode Discharge Power DoE Investigation Summary

DoE methods were used to investigate the affects of gas temperature, gas flow rate and filter loading on the Autoselective glow discharge power generated using an inserted electrode configuration. The investigation showed the discharge power was affected by all of the investigated factors. A regression model was developed from the experimental data and was found to predict the discharge power with an accuracy of 7% within the design space investigated.

The regeneration rate was shown in a number of investigations to be proportional to the Autoselective discharge power. However, under exhaust-like conditions the gas flow characteristics were found to be also influential in determining the regeneration achieved. The following section discusses the response of the regeneration rate produced by an inserted electrode configuration to changes in the experimental factors during the DoE investigation.

6.10 Inserted Electrode Regeneration Rate Response

Statistical analysis of the regeneration rate data, using the Stat Ease Design Expert v.6.0.10 software, provided assessment of the quality of the experimental process
and the measured data, along with a response surface equation. The details of the analysis and the diagnostic results are given in Appendix A4.

6.10.1 Regeneration Rate Response Analysis

The regeneration rate data was found to be free from erroneous trends and outlying points. The data showed that the gas temperature, gas flow rate and the filter loading had statistically significant influence on the regeneration rate achieved by the inserted electrode. The regression process of the DoE investigation provided the linear response surface model:

\[
g_{\text{hr}^{-1}} = 0.1403 - 2.708 \times 10^{-6} V + 6.015 \times 10^{-5} T + 0.0284 L \quad \text{Equation 6-2}
\]

where \( V \) = gas flowrate \((\text{l.min}^{-1} @ \text{STP})\), \( T \) = gas temperature \((\text{K})\) and \( L \) = filter loading \((\text{g.l}^{-1})\)

Diagnostic analysis of the regression model showed that the experimental design was adequate to provide the model terms. The regeneration rate calculated data and measured data within the design space are compared in Figure 6-22.
Figure 6-22 - Regeneration rate response modelled data against measured data

The response surface model predicts the measured data within the design space with an minimum accuracy of 3%.

6.10.2 Regeneration Rate Results Discussion

The regeneration rate response graphs for each factor investigated with the inserted electrode are shown in Figure 6-23. The graphs support the conclusions from the statistical based Analysis of Variance (ANOVA) and regression model discussed above and in Appendix A4. The regeneration rate increased with increasing gas temperature and reducing gas flowrate, similar to the effects observed with the pin electrode configuration. As the filter loading increased the regeneration rate achieved by the inserted electrode configuration increased.
Figure 6-23 – Inserted electrode regeneration rate measured response to the investigated factors (a) gas flowrate, (b) gas temperature and (c) filter loading
The following discussion attempts to provide explanation of the physical causes of the variation in regeneration rate response observed as the levels of the investigated factors were changed. The regeneration rate was influenced by the Autoselective discharge power as shown in Figure 6-24, i.e. as discharge power increased the regeneration rate achieved increased. Since the power of the inserted electrode discharge was affected by the investigated experimental factors, the regeneration rate can be affected indirectly. The gas and filter conditions could also affect the regeneration rate directly by influencing the oxidation process. Thus the overall change in regeneration rate as the gas and filter conditions vary was likely to be a combination of the direct affects on the oxidation process plus the indirect affect through changes in the discharge power.

![Discharge Power Graph](image)

**Figure 6-24 - Inserted electrode measured regeneration rate and measured discharge power**

### 6.10.2.1 Affects of Gas Flowrate on Inserted Electrode Regeneration Rate

Figure 6-23(a) confirms that as the gas flow rate increased the regeneration rate decreased. A similar trend is evident when using the pin electrode configuration as discussed in Chapter 5. However, the regeneration rate of the pin electrode was
influenced to a greater extent by the gas flow rate than that of the inserted electrode. As the gas flowrate increased from 1600 l.min\(^{-1}\) @ STP to 4200 l.min\(^{-1}\) @ STP the regeneration rate using the pin electrode reduced by 12% whilst that of the inserted electrode reduced by only 3%.

The power of the discharge generated by the inserted electrode configuration reduced as the gas flowrate increased. As the flow rate increased, the charge losses from the plasma increased, resulting in a reduction in discharge power. This then resulted in a reduction in the regeneration rate. The reduction in the number of charged particles resulted in a reduction in the amount of energy transferred to the PM. The reduction in energy transferred increased the time taken to elevate the PM temperature to the ignition temperature. This affect was essentially the same as that believed to occur when using the pin electrode.

The obvious high level of disturbance to the pin electrode discharge caused by turbulent gas flow was not evident when using the inserted electrode configuration. The discharge appeared to be much more stable and less violently agitated. Thus the reduced discharge movement did not affect the residence time at each ground site as significantly in the inserted electrode case, resulting a lesser influence on regeneration rate. During pin electrode discharge testing the regeneration rate reduced by 12% between high and low flowrate conditions. Under the same gas conditions but using the inserted electrode the regeneration rate only reduced by 3%. The discharge power was affected to a greater extent by the gas flowrate when using an inserted electrode, compared to a pin electrode. However, even though the discharge power was reduced more significantly when using the inserted electrode configuration under high flowrate conditions, the lack of discharge disturbance meant that the regeneration rate was reduced to a lesser extent.
6.10.2.2 Affect of Gas Temperature on Inserted Electrode Regeneration Rate Response

Figure 6-23(b) shows that as the gas temperature increased the PM mass oxidation rate increased; a similar trend to that observed with the pin electrode configuration. As the gas temperature increased from 80 °C to 400 °C, the regeneration rate achieved by the pin electrode increased by 12% whilst that of the inserted configuration increased by only 8%.

The regeneration rate of the inserted electrode configuration increased by 8% as gas temperature increased from 80 °C to 400 °C, whilst the discharge power increased by only 5%. This non-proportional increase in regeneration rate may be accounted for by the elevation of the PM temperature by the high temperature gas. The higher initial temperature of the PM meant that less energy was required from the discharge to cause oxidation. Thus under high gas temperature conditions, a relatively high power discharge was generated whilst the PM actually required less energy from the discharge, to be oxidised. Therefore, the regeneration rate increased at a greater rate than the discharge power as gas temperature was increased.

6.10.2.3 Affects of Filter Loading on Inserted Electrode Regeneration Rate Response

Previous sections of this chapter describe how the discharge current increased as filter loading increased. The carbon element of the PM acts as a source of electrons within the electric field between the electrodes. The emitted electrons caused electrical breakdown to occur at a lower voltage compared to when the filter was clean. Then the electrons sourced from the carbon contribute to increase the discharge current once a discharge has been established. This increased current resulted in an increasing discharge power as the filter loading increased. The larger numbers of energetic particles within the plasma result in an increase in energy transfer to the PM at the discharge root, resulting in more rapid oxidation at higher filter loadings.
As the filter loading increases from 2 to 4 g.l\(^{-1}\), the average discharge power during the on time increased by 11%, whilst the regeneration rate increased by 26%. A number of active particulate filter regeneration systems discussed in published research have exhibited the tendency to produce self-sustained oxidation reactions at high filter loadings. The oxidation process is initiated by the regeneration system but the energy released by the exothermic combustion reaction ignites neighbouring PM. Some regeneration systems, mainly electrical heating and microwave systems (Nixdorf et al, 2001, Garner and Dent, 1989), have attempted to use this concept to reduce the total energy requirement and maximise the system efficiency. However, this can only be achieved when the filter mass loading is above a critical value. Below the critical loading, the energy release rate is not sufficient to maintain a self-sustained regeneration. There also exists an upper limit to the filter loading. Above this upper limit a self-sustained oxidation reaction can release enough energy to cause thermal damage to the filter structure. Thus the regeneration systems that use these self-sustaining reactions require careful control to accurately monitor filter loading. As discussed in Chapter 2, filter loading assessment under engine exhaust flow conditions is difficult to achieve.

The disproportionate increase in regeneration rate produced by the Autoselective system as filter loading increases, compared to discharge power, is believed to be due to regions of PM neighbouring the discharge root undergoing small-scale self-sustained regeneration reactions. The heat released whilst the discharge is operating and causing the oxidation of PM at its root is conducted into the neighbouring PM. As filter loading increases, the discharge contains more energy to deliver to its root region, and more PM is oxidised at each ground site. Both mechanisms result in increased energy that can be conducted into the neighbouring PM resulting in the propagation of the oxidation process. Thus the discharge causes the oxidation of the PM at the discharge root and also the PM in a region surrounding the ground site.

The average regeneration efficiency, the mass of PM that is oxidised per unit of discharge power, at each filter loading is shown in Figure 6-25. As the filter loading
increased, the regeneration efficiency increased. The energy within the discharge or released by the discharge oxidises a larger mass of PM per unit time. The small oxidation reactions that could occur around the discharge root as a result of the energy released during discharge operation cause this increase in regeneration efficiency. Effectively, the regeneration process continues when the discharge is been switched off, resulting in the greater than proportional increase in regeneration rate compared to the increase in discharge power.

![Graph showing regeneration efficiency vs. filter loading](image)

**Figure 6-25 - Average regeneration efficiency (g.kW⁻¹.hr⁻¹) using the inserted electrode configuration with 50 ms on and 50 ms off duty cycle at various filter loadings**

Thus the regeneration rate achieved using the inserted electrode configuration increases as the filter loading increases due to two mechanisms. The discharge power increases leading to an increase in the energy transferred to the PM, consequently increasing the mass oxidised per unit time. It is also believed that at relatively high filter loading conditions small regions of PM neighbouring the discharge root continue to oxidise after the discharge extinguishes. These small self-sustained regeneration regions are most likely to be initiated by heat conducted from the discharge and heat released by the PM oxidised directly at the discharge root.
6.11  **Inserted Electrode DoE Developed Model Validation**

The response surface equations developed from the DoE investigation require validation to provide some confirmation of the accuracy with which they could be used to predict the relevant response. The validation procedure involved using the model equations to predict the response at selected points within the design space. The response values at these points are then measured using the same procedure used in the DoE investigation. The points within the design space used in the validation procedure should not be points that were tested in the original experimental matrix as these have already been compared to the model. The validation runs provide further data as to the accuracy of the model in predicting the response within the design space.

The factor levels chosen to confirm the validity of the model are the mid points between those which make up the majority of the D-Optimal design matrix, similar to those points used for the pin electrode model validation (see Figure 6-26).

![Candidate runs for DoE matrix](image)

**Figure 6-26- Inserted electrode experimental design space investigated using DoE techniques**

The experimental runs in the validation procedure are shown in Table 6-5, along with analysis of the results comparing the modelled and measured response data.
### Table 6.5 - Inserted electrode response surface model validation procedure results and analysis

The variance between the measured and predicted values investigated within the validation runs is graphically illustrated in Figure 6-27. No trends are evident within the validation run variance. This indicates that the variation is due to random experimental errors introduced into the measured data. Such errors within the data from which the response surface models are developed will introduce variance. Similar experimental errors can then compound or reduce the variance between the predicted and measured responses from the validation runs.
Figure 6-27 - Predicted against measured inserted electrode response data. (a) regeneration rate and (b) discharge power during on period of the duty cycle

During the validation runs the regeneration rate achieved using the inserted electrode configuration was predicted with an accuracy of +/- 3%. The average discharge power during the on period of the duty cycle can be predicted to within +/- 5%. During the DoE investigation the regeneration rate predicted values were within approximately 3% of the measured data, whilst the discharge power model predicted the measured data with an accuracy of 7%. The accuracy of the response surface models in the DoE investigation and the validation runs are in agreement.
The regeneration rate achieved by the inserted electrode configuration can be predicted to within 3% of the measured values, whilst the average discharge power during the duty cycle on period can be predicted with an accuracy of 7%.

6.12 Inserted Electrode Investigation Summary

The DoE investigation of the factors that affect the inserted electrode operation showed that the gas flow rate, the gas temperature and the filter loading influence the discharge power and regeneration rate. The changes in discharge power change the energy transferred to the PM and consequently change the regeneration rate. The oxidation performance is also affected directly by the gas flow rate, gas temperature and the filter loading.

The inserted electrode average discharge power measured during the duty cycle on period was approximately 11 W, with a maximum of 12.6 W and a minimum of 9.5 W. The discharge power increased with gas temperature and reduced with gas flow rate, however, the filter loading was found to be the most influential factor. The PM was believed to act as a source of electrons that aid the ionisation processes, leading to increased discharge current and therefore power as filter loading increased.

The average regeneration rate of a single Autoselective discharge generated by an inserted electrode and operating with a 50 ms on and 50 ms off duty cycle was 0.25 g.hr⁻¹. The minimum regeneration rate measured during tests was 0.20 g.hr⁻¹ under high flowrate, low temperature and low filter load conditions. The maximum regeneration rate measured was 0.29 g.hr⁻¹ when the gas temperature was relatively high, the gas flowrate was at its lowest limit and the filter loading was high. The filter loading was again the most influential factor, through both its influence in increasing the discharge power and the small scale sustained regeneration reactions, which are believed to continue once the discharge extinguishes.
The DoE investigation provided data from which response surface equations were developed to model the discharge power and regeneration rate under the conditions within the experimental design space. These models were validated within the design space under investigation. Comparing the response values predicted by the models to the empirical data showed the discharge power could be predicted with an accuracy of 7% whilst the regeneration rate could be predicted to an accuracy of 3%.

The Autoselective regeneration system, using an inserted electrode configuration, was shown to regenerate a diesel particulate filter in an environment similar to that experienced in a diesel engine exhaust, without causing damage to the filter structure.

The next chapter discusses a number of investigations that aimed to identify features and trends within the regeneration process initiated by the inserted electrode Autoselective discharge system. The chapter then discusses the testing of a prototype discharge system, on a dynamometer loaded engine, that aimed to validate the data measured in HFR testing. The chapter then concludes with a comparison of the Autoselective system to other diesel particulate filter regeneration systems discussed in published research. The chapter highlights the advantages of the Autoselective system identified by this research and the requirement for further work to develop an electrical power supply to exploit the Autoselective system’s potential.
Chapter 7 - Application of the Autoselective System

7 Performance and Application of the Autoselective System

This chapter presents an investigation of the oxidation process using a mass spectrometer to provide an assessment of the products of regeneration. The investigation also shows some of the differences caused by changes to the discharge as the filter is regenerated using the inserted electrode configuration.

A quasi-continuous gravimetric assessment technique is then discussed to identify time-based trends within the regeneration process. The time-based trends, if used within a control strategy, could provide a means to minimise the energy required for filter regeneration in a practical system.

The pressure mapping technique, previously discussed in Chapter 4, is then used to provide assessment of how the regeneration process affects the local back-pressure profile within the filter.
7.1 Mass Spectrometer Analysis of Regeneration Emissions

Electrical discharge plasma contain large numbers of particles released from ionisation processes. These particles are energised by the applied electric field in the discharge gap giving them the capability to cause changes to the background gas or contacting surfaces. This process causes the PM at the root of the Autoselective discharge to become heated and oxidised. However, the energetic particles can cause reactions within the background gas, leading to the emission of by-products.

Exhaust aftertreatment devices should not cause the emission of noxious products during the treatment of the engine exhaust gas. This requirement can lead to certain limitations on the situations in which some aftertreatment systems can operate. For example the CRT particulate filter regeneration system (discussed in Chapter 2) has a low sulphur fuel requirement. This is because platinum catalyst within the CRT system oxidises fuel borne sulphur, leading to sulphate particulate emissions. The CRT system is therefore limited to operation with fuel with maximum sulphur content of approximately 20 ppm.

The ability of plasma to cause alterations in the composition of gases is used in a number of applications including the treatment of gaseous emissions from combustion processes and the generation of reactive species to enhance chemical processes. A field of research known as plasma chemistry has developed to exploit this ability of plasmas. However, this ability can cause the production of chemical species as by products to the main useful reaction under some circumstances. Such by products can be undesirable, especially from aftertreatment devices that pass them into the atmosphere.

The gaseous emissions from the Autoselective system, therefore, required investigation to ensure that they did not include noxious or regulated species. The investigation of the emitted species could also be used to provide assessment of the regeneration rate achieved by the Autoselective system. Measurement of the carbon containing compounds allows a carbon balance analysis to calculate the amount of
carbon oxidised. Measurement of the amount of CO₂ and CO downstream of the Autoselective system allows calculation of the amount of carbon PM oxidised:

\[
\begin{align*}
C + O₂ & \rightarrow CO₂ \\
C + O & \rightarrow CO
\end{align*}
\]

Equation 7-1

7.1.1 Mass Spectrometer Operating Principles

Mass spectrometers provide a means to measure the concentration of given species or compounds in their gaseous form. Mass spectrometers can produce a spectrum showing the constituents within a sample under investigation. Alternatively the mass spectrometer can be used to monitor the concentration of species of particular interest, for example CO₂.

The mass spectrometer does not actually measure the molecular mass directly, but rather the mass to charge ratio of the ions formed from the sample. A schematic of the functional components of a mass spectrometer is illustrated in Figure 7-1. The ions are formed within the ionisation chamber by bombarding the sample gas with high-energy electrons. The ions are then accelerated through some form of selector that sorts the ions according to their mass to charge ratio. The sorted ion stream is collected by a detector, which converts the ion flux into a proportional electric current called the ion current. A PC based data system records the ion current magnitudes and produces a mass spectrum or provides a spectral interpretation to identify compounds using on-line libraries.

![Figure 7-1 - Functional components of a mass spectrometer](image)

Mass spectrometers are generally differentiated by their selector system. The ions formed within the ionisation chamber are accelerated by an electric field. The
velocity to which each ion is accelerated is proportional to its mass. The accelerated ion stream then passes through a magnetic field that causes the stream to deflect. The trajectory of each particle is curved to an extent that depends upon its velocity, and therefore its mass. The various ionic compounds follow different trajectories causing them to strike different regions of the detector.

Double focusing mass spectrometers use a combination of magnetic and electric fields to focus and filter ions, providing sufficient resolution to separate ions of the same nominal mass but different chemical formulae. C2H4, N2, and CO, for example, all have nominal mass of 28, but the ‘exact’ or high precision masses are 28.0313, 28.0061 and 27.9949 respectively.

However, the investigation of the Autoselective system used a Pfeiffer Thermostar quadrupole mass spectrometer. Quadrupole mass filters consist of four parallel poles or rods. Particle mass sorting is dependent upon ion motion resulting from simultaneously applied constant electric fields and radio frequency electric fields. Scanning is accomplished by systematically changing the field strengths, thereby changing the mass to charge ratio that is able to reach the detector. Quadrupole mass spectrometers provide lower resolution than double focusing instruments but are more easily interfaced to various inlet configurations and much less costly.

7.1.2 Mass Spectrometer Investigation of Autoselective Discharge Emissions

Mass spectrometers can be used to identify the constituents of a gaseous mixture or to quantify the concentration of given species within a known gas flow. To achieve this concentration measurement the mass spectrometer ion current must be calibrated using gas samples of known concentration.

The mass spectrometer investigation of the Autoselective system aimed to assess what were the main by products of the regeneration process. PM oxidation should result in CO2 emission and possibly CO from incomplete combustion reactions.
However, plasma systems are capable of causing numerous chemical reactions, therefore other potential emissions were also investigated such as NOx compounds and potentially more importantly CN compounds.

The Autoselective discharge was generated using the inserted configuration operating with a duty cycle to prevent filter damage. The filter was initially loaded to 4 g.l⁻¹ and was then regenerated within the HFR in a gas flow of 1600 l.min⁻¹ @ STP of air at 200°C. The discharge was operated for approximately 20 minutes to allow the discharge to pass through its various regimes (i.e. the ‘orange’ and ‘blue’ discharges as discussed previously in Chapter 6) as the local filter loading reduced.

The mass of PM oxidised per unit time using a single HV electrode under representative gas flow rates within the filter would lead to very low concentrations of CO2 downstream of the filter. Using a 5.66” diameter filter, gas flowrate of 1600 l.min⁻¹ @ STP and a regeneration rate of approximately 0.2 g.hr⁻¹, the Autoselective system should generate a maximum of 0.5 g.hr⁻¹ of CO2. The average CO2 concentration downstream of the filter would be between 4-5 ppm, below the minimum level measurable using the Thermostar mass spectrometer. Therefore, the measurement point or inlet to the mass spectrometer was moved closer to the point of operation of the Autoselective discharge. The capillary inlet tube of the mass spectrometer was inserted into an outlet channel between a single HV electrode and single ground electrode (see Figure 7-2). This measurement point ensured that the species emitted from the regeneration process caused by the Autoselective discharge could be sampled prior to significant dilution. Such a measurement point is not suitable for an investigation to quantify the concentration of given species. If quantification was the aim then the measurement point would be moved downstream to allow adequate mixing of all emitted compounds and thus their relative concentrations to be established. Complete quantification of the volume of emitted species also requires the total gas flowrate to be known accurately.
PM oxidation should lead to the emission of CO$_2$ and possibly some CO from incomplete combustion. However, CO$_2$ is found within the atmosphere, with an average concentration of approximately 340 ppm, although this value does exhibit seasonal changes. This ambient concentration meant the mass spectrometer recorded an ion current at all times whilst monitoring CO$_2$ molecular mass. Systems are available which can remove catalytically the ambient CO$_2$ upstream of a measurement point, but these were not available during this investigation. The ambient CO$_2$ simply provides a raised baseline ion current. Any increase in the ion current above this ambient level would indicate that CO$_2$ was produced during Autoselective system operation.

The ionised CO$_2$ molecule or molecular ion (CO$_2^+$) appears at mass to charge ratio 44. The electron impact ionisation process can fragment some of the CO$_2$ molecules. A fraction of the ions appear in the spectrum at values less than that corresponding to the molecular mass of CO$_2$. Cleavage of carbon oxygen bonds produces ionised carbon monoxide (CO$^+$) or ionised atomic oxygen (O$^+$) giving fragment ions at mass to charge ratios 28 and 16. Loss of two neutral oxygen atoms results in a fragment ion at ratio 12 for carbon (C$^+$) (see Figure 7-3). The number of fragment ions
produced is dependent upon the abundance of the source molecule, the strength of the bonds within the molecule and the energy of the ionising electrons. A quantification study should record the concentration of certain fragmentation ions to allow them to be added to the concentration of the molecular ion, thus providing a total concentration figure.

![Species Concentration](image)

**Figure 7-3 – Schematic of mass spectrum of carbon dioxide, CO₂. Carbon dioxide molecular ion, CO₂⁺ = 44. Fragmentation ions CO⁺ = 28, O⁺ = 16 and C⁺ = 12**

Plasma processes can cause chemical changes in the background gas as well as inducing chemical reactions such as the oxidation of PM. Simply monitoring a molecular mass within the mass spectrum may lead to erroneous identification of species of interest if another species generated by the plasma process has a similar molecular mass. Monitoring the concentration of fragmentation species of the molecular ion under investigation, alongside those of the potentially present species provides information concerning which species is present within the sample. For example CO₂, produced through PM combustion, and N₂O, a species possibly produced within the plasma, have identical nominal masses (see Table 7-1). But their fragmentation ions are different, and thus monitoring of these fragmentation ions allowed identification of which species were actually present within the emitted gases.
<table>
<thead>
<tr>
<th>Ion</th>
<th>Nominal Molecular Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂⁺</td>
<td>44</td>
</tr>
<tr>
<td>CO⁺</td>
<td>28</td>
</tr>
<tr>
<td>C⁺</td>
<td>12</td>
</tr>
<tr>
<td>N₂O⁺</td>
<td>44</td>
</tr>
<tr>
<td>NO⁺</td>
<td>30</td>
</tr>
<tr>
<td>N⁺</td>
<td>28</td>
</tr>
</tbody>
</table>

Table 7-1 – Nominal molecular masses of CO₂ and N₂O, along with their fragmentation ions

7.1.3 Mass Spectrometer Results

Figure 7-4 shows the ion current trace for molecular mass 44 (CO₂) recorded during Autoselective discharge operation where a period of ‘orange’ discharge generation was followed by a period of ‘blue’ discharge. The period of blue discharge operation closely followed the orange discharge operation and therefore the flow rate through the filter test section was likely to be very similar. Thus the CO₂ concentration would not be significantly influenced by changes to the gas flow rate through the test region as the filter was regenerated. These measurements using the Thermostar mass spectrometer showed increased concentrations of species of molecular mass 44 and 28 during Autoselective discharge operation. The concentration of species with molecular mass of 12 also increased. The concentration of species with molecular mass of 30 showed no change. This combination of concentration changes as the Autoselective discharge switches from operation to non-operation indicates that carbon dioxide is emitted during filter regeneration using the Autoselective system, not N₂O. Concentration of CO, molecular mass 28, was also found to increase. The CO could have been emitted from the regeneration process, it could possibly be the fragmentation ions from CO₂ ionisation or some mixture of the two sources.
Individual mass spectrometers produce characteristic amounts of fragmentation ions for each primary species they analyse. The proportion of fragmentation ions is determined by the energy of the bombarding electrons and the species under investigation. Therefore, if the proportion of CO+ fragmentation ions produced during analysis of CO₂ could be established, the source of the CO present in the mass spectrum could be determined.

A sample gas consisting of 40% CO₂ and 60% Argon (molecular mass = 39 (Çengel and Boles, 1998)) was used to establish the ratio of CO₂ molecular ions to CO+ and C+ fragmentation ions produced by the Thermostar mass spectrometer. Since no CO or C compounds were present within the controlled sample gas, the compound concentration at molecular masses 28 and 12 could only be CO+ and C+ fragmentation ions. The ion current at molecular mass 28 (CO+) was between 7-9% of that at molecular mass 44. The ion current at molecular mass 12 (C+) was between 4-5% of that at molecular mass 44.

The change in ion current, above ambient levels, for the various molecular masses is shown in Table 7-2. The fragmentation ions produce ion currents of similar...
percentages observed during investigation of the control sample gas. This indicated that the concentration of species at molecular mass 12 was likely to be due to fragmentation of CO$_2$ molecules. The ratio of CO ion current, at molecular mass 28, to CO$_2$ ion current was approximately 1% above that found during the control gas investigation. Small concentrations of CO may have been emitted during the regeneration process. Further investigation of such concentrations would require a higher resolution device than the Pfeiffer Thermostar, possibly a double focusing mass spectrometer as discussed previously.

<table>
<thead>
<tr>
<th>Species</th>
<th>Molecular Mass</th>
<th>Orange Discharge</th>
<th>Blue Discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Ion Current (A)</td>
<td>% of CO$_2$ Ion Current</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>44</td>
<td>7.60 x 10$^{-7}$</td>
<td>-</td>
</tr>
<tr>
<td>CO</td>
<td>28</td>
<td>7.63 x 10$^{-8}$</td>
<td>10.0</td>
</tr>
<tr>
<td>C</td>
<td>12</td>
<td>4.06 x 10$^{-8}$</td>
<td>5.3</td>
</tr>
</tbody>
</table>

Table 7-2 – Change in ion current during Autoselective discharge operation

7.1.4 Comparison of Performance of Different Discharge Types

Figure 7-4 shows the concentration of CO$_2$ emitted by the Autoselective system during regeneration of the particulate filter, generating an 'orange' and 'blue' discharge. The CO$_2$ ion current during orange discharge operation was approximately 8 times greater than that emitted during blue discharge operation. This indicates that the oxidation of PM was substantially lower during blue discharge operation compared to orange discharge operation.

The orange discharge was predominantly generated during relatively high filter loading conditions. As the filter is regenerated and the loading level reduces the blue discharge becomes predominant. Therefore, under relatively high initial filter loading conditions the regeneration rate was higher than that observed once the filter was partially regenerated.
Chapter 7 - Application of the Autoselective System

7.1.5 Mass Spectrometer Investigation Summary

The mass spectrometer investigation of the combustion emissions from the Autoselective discharge during filter regeneration showed that much of the PM was oxidised to produce CO₂. Incomplete combustion of PM to produce CO appeared to be very small if it occurred at all.

Comparing the CO₂ emissions emitted during orange and blue discharge generation indicated that the orange discharge produced a much higher regeneration rate than the blue discharge. The mass spectrometer used in the investigation was not of sufficient resolution to allow a quantified investigation of the total regeneration rate.

The following section discusses a technique developed to gravimetrically quantify the regeneration rate achieved during extended Autoselective discharge operation, to quantify time-based trends within the regeneration rate.

7.2 Quasi-Continuous Mass Measurement

The mass spectrometer investigation showed that the Autoselective discharge oxidises PM to produce mainly CO₂. The investigation also showed that the ‘orange’ discharge was more effective at oxidising matter than the ‘blue’ discharge, which occurred at lower loading levels. However, the Thermostar mass spectrometer’s resolution was insufficient to provide a means to quantify the regeneration rate or identify time-based trends.

Observation of the Autoselective system using the inserted electrode configuration showed that if the initial loading was sufficient, a distinctly ‘orange’ glow discharge was generated within the filter. As regeneration progressed and the local filter loading reduced the orange discharge was interspersed with an increasing proportion of blue discharge. The two discharge types resulted in different CO₂ emission levels, indicating the regeneration rate was changing.
This section explains a novel technique and apparatus that enabled the assessment of the regeneration rate over short periods of time and thus provided an insight into how the regeneration rate changed as the wall flow filter was regenerated.

### 7.2.1 Quasi Continuous Mass Measurement Experimental Arrangement

An experimental apparatus was developed to allow quasi continuous mass measurement of a filter test section regenerated with an Autoselective discharge from an inserted electrode configuration and duty cycle to prevent filter damage.

A filter test section was suspended in the airflow of the HFR. The end plug sections from each end of the test filter were carefully removed to allow gas flow through the channels. The end plugs would prevent gas flow passing through the filter test section, and create non-representative conditions. The flow through the test section channels was not exactly the same as that through an intact normal filter. The channel axial and wall or filtration velocities from the test section are compared to those of the standard filter in Table 7-3. The filtration velocity here is defined as the gas velocity through the total filtration area of the wall flow filter normal to the wall and is a determining factor in filter backpressure and filtration characteristics.

<table>
<thead>
<tr>
<th></th>
<th>Test Section</th>
<th>Full Wall Flow Filter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial Flowrate</td>
<td>4200 l.min⁻¹ @ STP</td>
<td>Up to 4200 l.min⁻¹ @ STP</td>
</tr>
<tr>
<td>Average Filtration Gas Flow Velocity</td>
<td>0 cm.s⁻¹</td>
<td>0 - 4 cm.s⁻¹</td>
</tr>
</tbody>
</table>

Table 7-3 - Comparison of flow velocities through the continuous mass measurement test section to those through a normal full wall flow filter

The test section without end plugs did not force the gas flow to pass through the filter section walls, thus the filtration velocity was not replicated. However, the channel axial velocity was replicated. This axial flow, which was perpendicular to the direction of the discharge was believed to be the most influential flow
component upon the discharge operational characteristics, as discussed early in this Chapter. The gas velocity at the filter section exit was measured using a pitot tube.

The test section (see Figure 7-5(a)) was supported within the gas flow via a structure positioned on the top pan of a Sartorius 124S analytical balance (see Figure 7-5(b)), with a resolution of 0.1 mg. The general assembly of the experimental setup is shown in Figure 7-6.

![Diagram of the experimental setup](image)

**Figure 7-5** - Filter test section support structure for continuous mass measurement

(a) loaded filter test section with inserted electrodes (b) analytical balance apparatus
7.2.2 Quasi Continuous Mass Measurement Results

The filter test section, taken from a filter pre-loaded to 3 g.l⁻¹ was regenerated under constant flow conditions for two minutes by an Autoselective discharge generated using an inserted electrode configuration. The discharge was extinguished after two minutes, the flow terminated and the filter test section mass measured from the analytical balance. Care was taken to ensure that the support structure that passed through a hole in the hot flow rig was not being fouled. Such fouling would cause errors in the mass measurement of the test section and thus lead to errors in the calculated regeneration rate.

The graph of the calculated regeneration rates achieved at intervals of two minutes in a twenty-minute test is shown in Figure 7-7.
The graph shows that the regeneration rate achieved by the Autoselective discharge changed throughout the twenty-minute test. Initially the 3 g.l⁻¹ filter loaded section was regenerated at a rate equivalent to 0.27-0.25 g.hr⁻¹ for approximately eight minutes. After twenty minutes of operation under flow and using a 50 ms on, 50 ms off duty cycle the regeneration rate fell to approximately 0.15 g.hr⁻¹. Within the period from eight minutes of operation to fifteen minutes the regeneration rate steadily reduced as the region surrounding the HV electrode was regenerated and the discharge changed regime.

The regeneration rate pattern follows the observed discharge type or regime pattern within the filter. Initially when the local filter loading was 3 g.l⁻¹ the orange discharge was generated achieving a relatively high regeneration rate. Towards the end of the twenty-minute test period only the blue discharge was observed within the filter and the regeneration rate has reduced to 0.15 g.hr⁻¹. After the first six minutes of the test the blue discharge is occasionally observed interspersing the orange discharge. As the test continued the proportion of time in which the blue discharge was operating increased as the local filter loading reduced below the 1.8
Chapter 7 - Application of the Autoselective System

g.l\textsuperscript{1}\ required to initiate and sustain the orange discharge using a 10-12 kV pk-pk, 20 kHz sinusoidal output power supply.

Analysing the data further allowed the regeneration efficiency of the orange and blue discharges to be calculated throughout the test period (Figure 7-8). The regeneration efficiency was calculated from the regeneration rate achieved and the average discharge power recorded by the digital oscilloscope.

![Figure 7-8 - Regeneration efficiency calculated from quasi continuous mass measurement](image)

Investigation of the performance of different types of discharge, discussed in Chapter 5, showed that a given discharge regime produced a characteristic regeneration efficiency time history. Whilst regeneration rate was affected by discharge power, the regeneration efficiency appeared to be only dependent upon the discharge regime in operation. Comparing those results with Figure 7-8 indicated that all the discharges generated were glow type discharges. Initially the orange discharge had high regeneration efficiency, even compared to that of the glow discharges generated during the discharge selection investigation. The inserted electrode configuration appeared capable of generating highly efficient glow discharges.
discharges in terms of their ability to oxidise PM. As regeneration progressed and the filter loading reduced the blue discharge became more prevalent. The regeneration efficiency figures indicate that this blue discharge is still a form of glow discharge. The discharge current traces indicated that the discharges were not pure examples of any of the discharge regimes, but the orange discharge resembled the glow discharge electrical characteristics. The current trace from the blue discharge contained more signs of corona type characteristics with the large number of filamentary components within the current but still exhibited a distinctly sinusoidal form.

7.2.3 Implications of the Inserted Electrode Autoselective Discharge Regimes

The mass measurement technique showed that the rate at which the Autoselective discharge oxidised PM reduced substantially after approximately 6-8 minutes of operation in a 3 g.l⁻¹ loaded filter. However, the power consumed by the Autoselective discharge generated using the inserted electrode configuration reduced by approximately only 1 W from 10.5 W (see Figure 7-9). Therefore the energy efficiency of the Autoselective systems reduces with time, as discussed above.
Figure 7-9 - Inserted electrode average discharge power at intervals of two minutes from measurements taken during quasi continuous mass measurement investigation

In a practical system the use of an overall operating cycle may allow the energy efficiency of the system to be maximised. If the discharge is only operated in the highly efficient glow regime, indicated by an orange discharge and few filamentary elements within the discharge current, then the energy efficiency will be maximised. The primary factor that determined the type of glow discharge in operation was the filter loading. If the discharge were only to be operated when the filter loading is above 2 g.l⁻¹ and only operated for short periods (~ 5-10 minutes), then the discharge would only operate in the most efficient part of the glow regime. This operational cycle would minimise the energy requirement to regenerate the filter using the inserted electrode configuration to generate the Autoselective discharge.

Monitoring filter loading can be achieved using a number of methods briefly discussed in Chapter 2. Such methods could be developed further to allow the Autoselective discharge to be initiated only at the appropriate loading. The discharge characteristics could be monitored to allow assessment of when the
discharge switches from the glow to corona regime or the discharge could simply be operated for a predetermined length of time.

### 7.2.4 Quasi Continuous Mass Measurement Summary

The continuous mass measurement technique showed that the regeneration process was not linear with time. A significant proportion of filter regeneration occurred in the first 8 minutes of discharge operation, corresponding to operation in the regime closest to a pure glow discharge. As the filter was regenerated the discharge current form altered, becoming further out of phase with the applied voltage and containing more filamentary elements, resulting in reduced regeneration rate and regeneration efficiency. The discharge also changed in appearance as previously noted.

The non-constant regeneration rate introduced the possibility of Autoselective system operation using an overall duty cycle, in addition to the 50 ms on; 50 ms off cycle used to prevent filter damage. The overall duty cycle could ensure the discharge only operated in the highly efficient part of glow regime, maximising energy efficiency and regeneration rate. However, application of this duty period would require a method to evaluate the filter loading, which would add cost and complexity to any practical solution.

### 7.3 Regeneration Progress Analysis Using Pressure Mapping Techniques

The continuous mass measurement apparatus allowed assessment of the time-based trends within the rate at which PM was oxidised by the Autoselective discharge. The oxidation of PM by the Autoselective discharge from the wall flow filter causes the local backpressure to reduce, regenerating the filter.

The changes in the local backpressure were assessed using the pressure mapping technique described in Chapter 4. The gas flow rate through individual filter outlet
channels was indicated using a small, modified Kiel probe. The stagnation pressure of this outlet channel gas flow was measured using a digital manometer with a 1 Pa resolution.

The size of the Kiel probe compared to the channel disrupted the flow to the extent where accurate quantative flow rate assessment was not possible. However, the stagnation pressure measurements did provide a repeatable and reliable indication of the flow rate through each outlet channel, and consequently the local back pressure changes caused by the regeneration system.

Figure 7-10 shows eight pressure maps measured after defined periods of regeneration using an inserted electrode configuration in a filter with 3 g. l$^{-1}$ loading. The discharge operated with a 50 ms on; 50 ms off duty cycle in a gas flow of 2800 l.min$^{-1}$ @ STP at 200 °C within the HFR. The flow rate through the rig was monitored and kept constant using the flow control valve within the HFR.
Figure 7-10 - Pressure maps illustrating the affects of the Autoselective discharge on the local filter back pressure profile around the inserted HV electrode

(Measured units, Pa)

The local backpressure profiles clearly illustrate that regeneration progressed in a radial pattern out from the HV electrode. As time progressed the regenerated area
increased, simultaneous to more effective or complete regeneration of the channels close to the HV electrode. However, the proportion of the overall gas flow passing through a given channel was determined by its backpressure relative to the other channels in the filter. The gas flow found steady state equilibrium for each channel. The flowrate through a given channel was dependent upon the overall flowrate though the filter and the relative backpressure imposed by each channel within the filter.

As such as the regeneration area increased, the flowrate through previously regenerated channels decreased. Using a DC electrical circuit analogy (see Figure 7-11) where the voltage is representative of the flow pressure, the current is representative of the flow rate and the electrical resistance is representative of the flow resistance.

![Figure 7-11 - Flow path resistances depicted by electrical resistance analogy](image)

The voltage across all resistors is the same; as the back pressure across each channel in the filter is the same. The relative resistance of each parallel resistive element determines the current carried through each electrical resistor or the gas flow rate through each channel.

Table 7-4 shows how the current through each resistor in the circuit shown in Figure 7-11, changes as the relative resistance of each element in the circuit varies. The total current flowing between points A and B remains constant, but the distribution through each resistive element is dependent upon its relative resistance to the other elements in the circuit.
Table 7-4 illustrates that as the relative resistance of a single element reduces, the current through that element increases whilst the current through the other elements reduces. However, as the total number of low resistance elements increases, the current through each of these elements reduces.

Similarly, as the regenerated area increases the flowrate through the first channels to be cleaned, next to the HV electrode, should reduce. However, this is not evident from the pressure maps. The flow rate through the channels next to the HV electrode that were regenerated first, continued to rise even as the regenerated area increased. This increase in flow rate showed that the channels next to the HV electrode continued to be regenerated as channels further from the HV electrode began to be regenerated. The discharge did not completely regenerate the filter channels closest to the HV electrode before moving to channels further from the HV electrode. The channels closest to the HV electrode were only partially regenerated before those channels in the next layer of filter began to be regenerated.

This regeneration pattern shows that the lowest impedance path to ground for the discharge was not always the path via the PM that was in closest proximity to the HV electrode. The close proximity PM may have been connected to ground via an extended or high resistance path compared to the PM that was further from the HV electrode.
7.3.1 Regeneration Progress Pressure Mapping Summary

The Autoselective discharge generated using an inserted electrode and operating with a duty cycle produced an approximately radial regeneration pattern centred on the HV electrode. The discharge did not completely regenerate the channels nearest the HV electrode before extending radially out. The path of lowest impedance for the discharge to ground sometimes caused the discharge to bypass the PM that was in closest proximity to the HV electrode. This by-passing occurred approximately once every 10 seconds during the first two minutes of operation and increased with time as regeneration progressed.

All of the investigations described in the previous sections of this Chapter provided an understanding of the Autoselective system operating with an inserted electrode configuration. The electrode configuration and duty cycle were developed to maximise the regeneration rate achieved by the Autoselective discharge whilst preventing it from damaging the filter. These investigations allowed the development of an early on-engine prototype to validate the findings made using the HFR. The on engine testing also provided insight into some of the practical issues that need to be addressed before the application of the Autoselective system.

7.4 On-Engine Testing of The Autoselective System

The regeneration rate of the Autoselective system had been investigated under exhaust like conditions in the HFR. However, as previously discussed, the HFR did not exactly replicate the conditions within a real engine exhaust gas flow. Verification was required of the regeneration rate achieved in a real engine exhaust by the Autoselective discharge inserted electrode system.

A prototype power supply was developed to provide the required high frequency sinusoidal voltage waveform, and then step this up to the required discharge voltage
using high frequency transformers (see Figure 7-12). The design details of the power supply will not be discussed in detail. However, the supply was still only a prototype system that was unlikely to resemble any final design but did provide a more practical means to test the Autoselective discharge in the exhaust of an engine.

![Diagram showing high frequency driver circuits, high frequency transformers, and HV electrodes.](image)

**Figure 7-12 - Prototype power supply used for Autoselective system on engine testing**

The electrical waveforms were identical to these produced by the experimental power supplies, used in laboratory testing, at 20 kHz and around 12 kV pk-pk. The correct operation of the power supply was confirmed through comparison testing on the HFR with the experimental power supplies used for the majority of the research. The discharge appearance and behaviour were identical, as were the regeneration rates and patterns, confirming the prototype power supply provided the required Autoselective discharge characteristics.

The power supply consisted of eight 20 kHz, high voltage drive circuits and transformers. Each transformer was connected to a single copper, HV electrode that was inserted into a clean 5.66" (143 mm) diameter and 6" (152 mm) long Cordierite wall flow filter. Hexagonal configuration ground electrodes were inserted from the upstream side of the filter surrounding each HV electrode (see Figure 7-13). The HV
to ground electrode separation was 20 mm in order to maximise the coverage of a single HV electrode whilst maintaining maximum regeneration rate.

Figure 7-13 - Filter canister and HV electrodes inserted into the centre channels of a 20 mm hexagonal configuration, from the rear of the 5.66" diameter filter for on engine testing

The filter was inserted into a specifically designed canister (see Figure 7-14). The HV electrodes were inserted through a Macor ceramic plate, which provided a gas sealing surface whilst preventing the HV electrodes from contacting and thereby electrically short circuiting to the metallic canister.
The test engine was a 4 cylinder, 4 stroke, 4.4 litre, turbocharged development common rail diesel engine. As such the 5.66" filter was typically too small for this size of engine operating on a real drive-cycle. However, the engine operating speed was maintained sufficiently below rated conditions to provide representative flow rates and back pressure across a 5.66" filter. The engine-out PM mass levels were monitored throughout testing using an AVL smoke meter and maintained at 5.5 to 6 g.hr⁻¹, a level which a 5.66" diameter filter was likely to experience from a Euro IV compliant engine (Caterpillar Inc. Supplied Data, 2004).

The seven HV electrodes supplied by the power supply were known not to be able to produce a regeneration rate sufficient to reduce the overall filter backpressure to clean filter levels. However, if the regeneration performance produced in the HFR could be replicated, the rate of increase of backpressure would reduce. Increasing the number of power supplies and HV electrodes would then scale the overall regeneration rate to produce the desired filter backpressure reduction.
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The diesel engine operating point was maintained at 1500 rpm and 150 Nm load, which produced the desired average engine out PM level of 5.5-6 g.hr⁻¹. The operating condition was selected to provide the loading rate per unit volume of filter that was likely to be experienced in real operation.

The exhaust gas pressure on either side of the filter was monitored through the dynamometer test bed data logging system to assess the current filter loading. The filter backpressure against time is shown in Figure 7-15. The clean filter was initially loaded for 1 hour and 20 minutes at the set engine load and speed point. This period loaded the filter to approximately 3 g.l⁻¹. This loading was the point identified by the consulting engine manufacturer when a regeneration system would be initiated to prevent significant reduction on fuel economy caused by loaded filter backpressure.

The initial rapid increase in backpressure is associated with the deep bed filtration period that is observed with wall flow filters (Konstandopoulos et al, 1999). The first particulate to be trapped by a clean filter enters the porous ceramic walls, narrowing and eventually blocking some of individual pores (Konstandopoulos et al, 1999). After this brief period of deep bed filtration, the more usual filtration mechanism associated with wall flow filters, shallow bed filtration, becomes dominant. The

![Figure 7-15](image)

Figure 7-15 – Wall flow filter backpressure against time during on engine testing

The initial rapid increase in backpressure is associated with the deep bed filtration period that is observed with wall flow filters (Konstandopoulos et al, 1999). The first particulate to be trapped by a clean filter enters the porous ceramic walls, narrowing and eventually blocking some of individual pores (Konstandopoulos et al, 1999). After this brief period of deep bed filtration, the more usual filtration mechanism associated with wall flow filters, shallow bed filtration, becomes dominant. The
shallow bed filtration mechanism results in the reduced rate of increase of filter backpressure observed in the majority of Period 1 of Figure 7-15.

The filter back pressure record clearly shows that the rate of increase of backpressure reduced when the power supply was switched on and the Autoselective discharge was operational during Period 2 of Figure 7-15.

The power supply was then switched off to ensure the rate of increase in backpressure returned to its original value. This second period of loading whilst the power supply was switched off provided an indication that the filter structure had not been damaged during regeneration. If thermal damage had been caused to the filter, the holes within the ceramic walls would reduce the rate at which the backpressure increased as the filter loaded. The rate of increase of backpressure during Period 3 of Figure 7-15 was identical to that during Period 1. As such the reduction in the rate of increase of backpressure during Period 2 was caused by the operation of the Autoselective discharge oxidising PM and regenerating the filter.

7.4.1 On Engine Testing Data Analysis

Analysis of the backpressure gradient allowed estimation of the average regeneration rate achieved by the Autoselective discharge. The average fouling rate of the filter under the given engine conditions was measured to be 5.9 g.hr\(^{-1}\) using the AVL smoke meter. The rate of increase in backpressure during the power supply off periods was 2.29 kPa.hr\(^{-1}\). Therefore the average pressure increase per unit mass of emitted PM under the specified engine conditions was:

\[
\frac{2.29}{5.9} = 0.388 \text{ kPa.g}^{-1}
\]

Equation 7-2

The pressure increase whilst the power supply was switched on was 1.47 kPa.hr\(^{-1}\). Thus the power supply operation of the Autoselective discharge resulted in a reduction in the rate of backpressure increase of 0.82 kPa.hr\(^{-1}\).
This allowed the PM oxidation rate to be calculated; assuming the rate at which PM entered the filter was constant. The total PM oxidation rate was therefore:

\[
\frac{0.82 \text{kPa.hr}^{-1}}{0.388 \text{kPa.g}^{-1}} = 2.11 \text{ g.hr}^{-1} \quad \text{Equation 7-3}
\]

Since the on engine prototype power supply provided 8 active electrodes, the average regeneration rate per HV electrode was 0.26 g.hr\(^{-1}\). Under similar gas flow and loading conditions and average regeneration rate on the HFR had been measured as 0.28 g.hr\(^{-1}\).

The discharge current and voltage waveforms from one of the HV electrodes were monitored during the on engine testing to allow the average discharge power to be calculated and the discharge characteristics to be observed. The HV electrode under observation operated in the highly efficient, orange glow regime for approximately 85-90% of the test time. The discharge current waveform contained very few filamentary elements compared to those seen when the less efficient, blue glow discharge operated within the HFR. The initial loading period was sufficient to provide a trapped particulate mass to produce the high efficiency discharge throughout the test. The regeneration rate achieved by each HV electrode was insufficient to fully regenerate the volume of filter surrounding each HV electrode. A regenerated volume of filter provided a low resistance flow path and was thus quickly reloaded with PM. The local filter loading around each HV electrode was not reduced sufficiently to cause the discharge to switch to the corona regime.

The discharge power was calculated from the current and voltage waveforms during the discharge on period. The average discharge power during the on period of the duty cycle during the engine testing was 10 W, in reasonable agreement with the 10.8 W measured during HFR testing under similar conditions. The peak voltage and current values were also comparable.
The mass of the clean filter was measured prior to on engine testing, using an analytical balance. After testing was complete the wall flow filter was carefully removed from the canister and the mass measured again using the analytical balance. The final mass PM within the filter, following the complete testing cycle, was 21.85 g. This value was in good agreement with the filter mass calculated from the average loading and regeneration rates over the four hour test; i.e.

\[
(5.9 \text{g.hr}^{-1} \times 4.33 \text{hr}) - (0.26 \text{g.hr}^{-1} \times 8 \times 2 \text{hr}) = 21.387 \text{ g}
\]

Equation 7-4

The agreement between the measured final mass and the calculated mass from average loading rate and regeneration rate indicates the values of net loading rates calculated from filter backpressure trends were correct.

7.4.2 Engine Testing Results Comparison to DoE Model Predicted Responses

The on engine testing provided an opportunity to investigate the accuracy with which the response surface models, developed during the inserted electrode DoE investigation, predicted the Autoselective system performance in real conditions.

The gas flow and filter loading conditions during the engine testing are shown in Table 7-5.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas flowrate (L.min(^{-1}) @ STP)</td>
<td>1600</td>
</tr>
<tr>
<td>Gas Inlet Temperature (°C)</td>
<td>200</td>
</tr>
<tr>
<td>Filter Loading (g.L(^{-1}))</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 7-5 – Gas and filter loading conditions during engine testing
Inputting the conditions from Table 7-5 into the developed response surface models gives:

\[
\text{Regeneration Rate} = 0.1403 - 2.708 \times 10^{-6} V + 6.015 \times 10^{-5} T + 0.0284L
\]
\[
\therefore 0.1403 - (2.708 \times 10^{-6} \times 1600) + (6.015 \times 10^{-5} \times 200) + (0.0284 \times 3) = 0.25 \text{g.hr}^{-1}
\]

Equation 7-5

\[
\text{Power} = 9.121 - 2.172 \times 10^{-4} V + 1.611 \times 10^{-3} T + 0.5755L
\]
\[
\therefore 9.121 - (2.172 \times 10^{-4} \times 1600) + (1.611 \times 10^{-3} \times 200) + (0.5755 \times 3) = 10.7\text{W}
\]

Equation 7-6

The average regeneration rate during engine testing was measured as 0.27 g.hr\(^{-1}\), in close agreement with the 0.25 g.hr\(^{-1}\) modelled using the DoE response surface. The average discharge power during the on period was measured as 10 W, and the predicted value was 10.7 W.

The discrepancy in the modelled responses was due to a number of factors including the previously discussed inaccuracies that are introduced when models are developed from experimental data. Also as previously discussed, the HFR used to gather the data on which the models were based does contain differences compared to a real engine, which may influence the discharge power. These differences include unsteady flow affects introduced by the gas exchange process in reciprocating engines and the presence of small concentrations of chemical species derived from the combustion of the fuel.

Potentially, and importantly, when operating on the real engine exhaust the discharge remained in the highly efficient part of the glow discharge spectrum. The filter continued to be loaded as the discharge oxidised PM. The filter loading local to the HV electrode never decreased sufficiently to allow the discharge to move to the less efficient part of the glow discharge spectrum. Thus the discharge regeneration rate remained at the high level. Comparing the regeneration rate from engine tests to that found during the continuous mass measurement investigation, the values
indicated that only the high efficiency discharge was generated. During HFR tests the filter was not reloaded as it was regenerated by the discharge. The filter loading reduced and eventually the discharge type shifted along the spectrum to a less effective and efficient type of glow discharge. Thus the regeneration rate and discharge power responses measured during HFR testing were the average of those produced by the different types of glow discharge produced throughout the test.

However, the reasonable agreement between the inserted electrode Autoselective discharge measured responses from engine testing and those predicted by the DoE models indicate that the models are suitable for response prediction in real engine exhaust systems. The models could be used in the design of a particulate filtration system that uses the Autoselective regeneration system.

7.4.3 Conclusions and Summary of the On Engine Testing

The preliminary on-engine testing demonstrated that similar regeneration rates could be achieved in a real engine exhaust and in the HFR under similar gas and filter loading conditions. This confirmed that the HFR simulated the characteristics of an engine exhaust adequately to provide valid results for the investigation of the Autoselective system's performance.

The testing demonstrated that an inserted electrode configuration could generate an Autoselective glow discharge, operating with a duty cycle, and that this discharge regenerated the wall flow filter without damage. Full filter regeneration was not demonstrated due to limited number of HV electrodes that could be driven by the prototype power supply used. However, simply increasing the power supply capacity and the number of HV electrodes would allow regeneration of the full filter volume.
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7.5 Analysis of Inserted Electrode Autoselective System Performance

The confirmation that the HFR accurately simulated the characteristics of a diesel engine exhaust allowed the results from the prototype investigations to be analysed further to estimate possible final system performance.

Assuming a fouling rate of 5.5 g.hr\(^{-1}\) (data supplied by Caterpillar Inc, 2004) and a regeneration rate per HV electrode of 0.25 – 0.27 g.hr\(^{-1}\), the system would require 21-22 HV electrodes. The average inserted HV electrode discharge power was measured as approximately 10 W, thus total discharge power would be 210 – 220 W to oxidised the engine-out mass of PM.

The implications of this discharge power demand on fuel economy depend upon a number of factors, including the efficiency of the power supply and the efficiency of the engine’s electrical system. Using the conservative estimates for the efficiency of a high voltage, high frequency power supply of 70 % and an alternator efficiency of 65%, the power demand from the engine can be estimated. The total power demanded from the engine by the Autoselective system producing 210 – 220 W of discharge power would be only 460 – 485 W to regenerate a diesel filter with a 5.5 g.hr\(^{-1}\) fouling rate. This compares very favourably with the power demanded by other particulate filter regeneration systems discussed in published research.

The following section extends this analysis by comparing the Autoselective system to other regeneration systems discussed in published research, and which were previously discussed in Chapter 2.

7.6 Regeneration System Comparison

Table 7-6 provides a summary comparison of the Autoselective system’s performance and limitations relative to other particulate filter regeneration systems.
from published research to date and previously discussed in greater detail in Chapter 2. The impending emissions legislation has spurred much research into particulate filters and their regeneration and as such provided an area in which many diesel engine manufacturers have sought to gain a technological advantage. As such many of the systems discussed below are likely to be at a further stage in their development compared to the information discussed in published research.

The ideal characteristics of a particulate filter regeneration system were listed in Chapter 2, and the review of published technologies showed that no system to date fulfils all of the requirements, and many introduce significant issues that are likely to make them unreliable. Table 7-6 shows that in many aspects of regeneration performance and system requirements the Autoselective system compares favourably with other regeneration systems. A number of very positive factors are likely to spur further research and development of the Autoselective system and these include:

1. insusceptibility to many of the environmental factors (e.g. gas flow rate, temperature, oxygen and water vapour concentration) experienced in the diesel engine exhaust; importantly the system does not require exhaust gas flow by passing during regeneration;
2. low power requirement;
3. highly developed, low cost power supply technologies. High frequency, high voltage power supplies that are a highly developed and low cost technology used for applications such as display screens;
4. simple regeneration control. The system was inherently Autoselective, operating most effectively and efficiently when PM was present within the filter.

These advantages are considered significant; no other system has many of these advantages. This suggests that the system has significant potential.
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### Advantages

<table>
<thead>
<tr>
<th><strong>Fuel Additives</strong></th>
<th><strong>Disadvantages</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Only a trap is required to filter the PM. No external energy input required and subsequent fuel economy reduction.</td>
<td>Requires automated system to deliver the fuel additive. Additive replenishment required during servicing. Potential release of fuel additives into the atmosphere. Build up of ash within the filter reducing PM loading capacity.</td>
</tr>
<tr>
<td><strong>Catalysed Filters</strong></td>
<td></td>
</tr>
<tr>
<td>Oxidises HC, CO and PM No external energy input required and subsequent fuel economy reduction Potential continuous regeneration</td>
<td>Potential emission of sulphate particles from fuel borne sulphur Requires low sulphur fuel Requires gas temperatures of 250-300 °C</td>
</tr>
<tr>
<td><strong>CRT (Using NO₂ to oxidise PM)</strong></td>
<td></td>
</tr>
<tr>
<td>Can oxidise PM at 250 °C. Potential continuous regeneration to minimise exhaust backpressure. No external energy input required and subsequent fuel economy reduction.</td>
<td>Requires sufficient NO₂:PM ratio. Potential emission of sulphate particles from fuel borne sulphur. Requires low sulphur fuels (&lt;20 ppm) to operate below 300 °C. Large physical size, difficult packaging into vehicles.</td>
</tr>
<tr>
<td><strong>Oxi-Exothermic Regeneration</strong></td>
<td></td>
</tr>
<tr>
<td>Abundant energy source (diesel fuel). Simple system control (engine management and FIE).</td>
<td>Potential problems with late cycle fuel injection and cylinder wall wetting. No regeneration control once initiated. Can increase engine out HC.</td>
</tr>
<tr>
<td><strong>Exhaust Gas Throttling</strong></td>
<td></td>
</tr>
<tr>
<td>No external energy system required. No special fuel requirement.</td>
<td>Can increase internal engine fouling by PM. Difficult regeneration control. Throttling system durability issues. Can significantly reduce fuel economy. Can increase engine-emitted noise.</td>
</tr>
<tr>
<td><strong>Fuel Burner System</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Electrical Heating System</strong></td>
<td></td>
</tr>
<tr>
<td>Rapid regeneration achievable if required. Do not require elevated gas temperatures. No special fuel requirement.</td>
<td>Close coupling of heating elements and filter can cause durability issues. Complex control system required to establish filter loading. Potential high temperature produced during uncontrolled regeneration.</td>
</tr>
</tbody>
</table>
## Chapter 7 - Application of the Autoselective System

- Electrical energy demand can require changes to engine/vehicle electrical system.
- Power requirement approx 2-3 kW (5.66” dia. filter). 2.5 - 4% of engine power during system operation.
- Usually requires exhaust gas bypass.
- Can require secondary air source to support oxidation.

### Microwave Regeneration System
- Rapid regeneration achievable if required.
- Does not require elevated gas temperatures.
- No special fuel requirement.
- Uneven regeneration.
- Even energy distribution can be difficult to achieve.
- Potential high temperature produced during uncontrolled regeneration.
- Power requirement approx 1 kW (5.66” dia. filter). 1-2 % of engine power during system operation.
- Can require exhaust gas bypass.
- Can require secondary air source to support oxidation.

### Plasma Regeneration Systems (NOx, oxygen and nitric radicals)
- Does not require elevated gas temperatures.
- No special fuel requirement.
- Can produce gaseous by products/secondary emissions.
- Many systems require special filter designs required to provide low space velocities to support chemical reactions.
- Low space velocities require large volume filter systems, causing packaging difficulties.
- Energy requirement approx 4-5% of engine power during system operation.

### Autoselective System
- Does not require elevated gas temperatures.
- No special fuel requirements.
- Operates with standard Cordierite wall flow filters.
- Operates in normal exhaust gas flowrates (i.e. does not require by pass).
- Low energy requirement during operation. 0.3-0.5% of engine power.
- Capable of regenerating filters at low filter loading, minimising risk of uncontrolled, self-sustained oxidation.
- Not yet capable of rapid regeneration if required.
- Safety implications of high voltage electrical systems on vehicles.

### Table 7-6 - Comparison of the Autoselective regeneration system with other regeneration systems discussed in published research. (Partly adapted from Kelly et al, 2001)

A number of the fundamental characteristics and trends within the Autoselective system’s performance were investigated. The system was confirmed to operate.
within the exhaust environment of a running engine, and assessment of the regeneration rate achieved provided validation of the results measured within the hot flow rig. Regeneration rate investigation showed that the different discharge regimes generated by the Autoselective inserted electrode configuration produce varying rates of PM oxidation. The trend was likely to be linked to the amount of PM within the filter and the affect on electron emission rates influencing discharge generation. The investigation showed that over half of the PM oxidised in a twenty minute period under flow conditions was oxidised in the first 6 minutes, presenting the possibility of operating the system intermittently to maximise efficiency and minimise energy consumption. Other investigations showed that the regeneration progressed from the HV electrode radially towards the surrounding ground electrodes and that the Autoselective system oxidised the trapped PM to produce carbon dioxide.

The following chapter provides a summary of the conclusions drawn from the investigations discussed throughout this thesis. The chapter then suggests key areas that require further investigation if the Autoselective system is to be developed into a practical solution for the regeneration of diesel particulate filters for meeting future emissions legislation.
8 Conclusions and Recommended Further Work

The research presented in this thesis studied the novel Autoselective discharge system and its effectiveness in regenerating Cordierite wall flow diesel particulate filters. The Autoselective discharge was produced using a high frequency, high voltage power supply connected to an electrode configuration that allowed the discharge to act upon the PM trapped in the wall flow filter.

The research considered some of the fundamental characteristics of the discharge and their influence on discharge performance in regenerating the filter. The performance of the discharge under the various gas conditions experienced within a diesel engine exhaust was investigated to establish the potential operating range of an Autoselective prototype system.

A comprehensive DoE investigation was completed to investigate the Autoselective system's performance under various exhaust gas flow conditions simulated by a hot flow rig. The DoE investigations resulted in the development of response surface
models to describe trends in the Autoselective discharge power and regeneration rate under various gas and filter loading conditions.

The investigations culminated in the development of a prototype system for on engine testing to validate the performance results measured during rig testing.

The Autoselective glow discharge was shown to regenerate wall flow diesel filters in the exhaust gas of a running diesel engine. An inserted electrode configuration allowed the discharge to regenerate the full length of a wall flow filter whilst using practical voltages.

### 8.1 Research Conclusions

This research has resulted in the identification of the fundamental characteristics and operating envelope in which Autoselective system can regenerate a Cordierite diesel particulate wall flow filter. During the research new measurement techniques were developed that allowed the progression and effectiveness of the regeneration process caused by the Autoselective system to be investigated further.

The important conclusions of this research are as follows:

1. The research demonstrated that the Autoselective discharge can oxidise PM from a Cordierite ceramic wall flow filter, thereby regenerating the filter for continual on engine further use.

2. The Autoselective discharge can be generated in the exhaust gas flow of a modern heavy-duty diesel engine.

3. The AC glow discharge regime was identified to produce the most effective plasma regime in terms of discharge energy efficiency in oxidising PM. The
alternating frequency was found not to be influential to the PM oxidation rate in the 10-100 kHz range.

4. The high density of charged particles accelerated through the root of the glow discharge caused a localised heating affect similar to that used in metal welding and cutting applications. This heating caused the trapped PM to be oxidised, producing mostly CO₂.

5. The length of the glow discharge generated using practical, safe power supplies was limited to approximately 20-25 mm in the engine exhaust environment. Inserting metallic wire electrodes into the channels of a wall flow filter caused the discharge to be generated perpendicular to the filter axis and thus allowed the 20-25 mm discharge to be able to regenerate the full wall flow filter length (~150 mm).

6. The glow discharge produced by the inserted electrode configuration was observed to often remain in a single position for an extended period (4-8 seconds). This extended period of operation in a single location increased the temperature of the ceramic filter to the extent where thermal damage was caused. Discharge power modulation in the form of an on/off period imposed on the power supply prevented the discharge from remaining in a single position and eliminated the thermal damage to the filter.

7. The Autoselective discharge regeneration performance was affected, to a limited degree, by the exhaust gas flowrate and temperature, but importantly was unresponsive to changes in gas oxygen and water vapour concentrations within the ranges of values likely to be experienced in a diesel engine exhaust gas flow.

8. The regeneration rate produced by the Autoselective discharge is proportional to the Autoselective discharge power. Increasing the glow discharge power resulted in increased regeneration rate, but also reduced the
time for which the discharge could be allowed to operate on the filter without thermal damage being caused. Increasing the discharge power resulted in greater numbers of energetic plasma particles passing through the discharge root and thus greater energy transfer to the PM at the discharge ground site.

9. The Autoselective glow discharge was shown to regenerate Cordierite ceramic foam deep bed filters under exhaust gas conditions. The discharge, generated using a pin electrode, regenerated to a 10-15 mm depth of the ceramic foam structure.

10. The affect of regeneration on the local backpressure of a wall flow filter was mapped using a modified Kiel probe. The novel technique provided a method to investigate regeneration progress and its affect on gas flow through the filter. The technique showed that filter regeneration using the inserted electrode configuration started at the central HV electrode and progressed out towards the ground electrodes.

11. A novel apparatus was developed that allowed the evaluation of time based gravimetric trends within the PM oxidation process. Quasi continuous mass measurements of a small section of loaded wall flow filter showed how different plasmas generated using the inserted electrode configuration produced significantly different regeneration rates. These data could provide the basis for the development of an operating cycle to maximise energy efficiency of a practical regeneration system.

12. A purely glow discharge produced in a filter loaded with more than 2 g.L\(^{-1}\) produced a maximum regeneration rate of 0.28 g.hr\(^{-1}\) when operating with a 50 ms on and 50 ms off duty cycle to prevent filter damage. As regeneration progressed the PM loading local to the HV electrode reduced and the discharge shifted to a mixture of corona and glow plasma, resulting in a reduced regeneration rate. This shift in discharge regime resulted in a
reduction in regeneration rate, confirmed by the quasi-continuous mass measurement technique.

13. The composition of the gaseous by products from the regeneration process was investigated using a mass spectrometer. The regeneration process produced by the Autoselective discharge lead to the emission of carbon dioxide \((\text{CO}_2)\) and no measurable quantity of carbon monoxide \((\text{CO})\) were detected.

### 8.2 Recommendations for Further Work

Having firmly established the fundamental operating characteristics and demonstrated the ability of Autoselective discharge to provide a practical, reliable, compact and energy efficient means to regenerate a diesel particulate filter a number of areas for further research have been identified. These include:

1. To fully exploit the advantages of the Autoselective discharge a suitable high frequency, high voltage power supply requires development and along with research concentrating on its integration into a vehicle’s electrical system.

2. The Autoselective discharge was shown to regenerate a wall flow diesel particulate filter without causing damage to the ceramic structure. However, the affects of numerous \((10,000+)\) load and regeneration cycles on filter ceramic structure require investigation to ensure filtration and backpressure characteristics of the filter are not degraded.

3. During the research brief tests were conducted which demonstrated the Autoselective discharge was capable of regenerating a ceramic foam deep bed filter. Ceramic foam filters can potentially offer a number of manufacturing, packaging and cost advantages over wall flow filters and may well become more widely applied as their filtration and backpressure characteristics are
developed. However, the optimum electrode configuration and operating cycle of the Autoselective system is likely to be different to that used for wall flow filters. The ceramic foams may be suited to the pin electrode or some similarly derived configuration, operating without a duty cycle. The shape and structure of the ceramic foam may be tailored to enhance the regeneration performance of the Autoselective system; all of these factors require investigation and consideration.
References


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Collins A, (2003), "Course Notes: An Introduction to Design of Experiments", Q D Consulting, acollins@qdconsult.co.uk


References


References


References


References


A1 DoE Analysis for the Pin Electrode Discharge Power Response

The following sections provide a description of the Analysis of Variance (ANOVA) technique and then its use in analysing the pin electrode discharge power response (discussed in Chapter 5). The ANOVA uses a number of statistical methods to identify which experimental factors are statistically significant in determining the response. The ANOVA process culminates in the development of a regression model to describe the discharge power response surface. A number of diagnostics statistics are then analysed to assess the quality of both the experimental design and the measured data to ensure they were adequate to develop a model within the selected confidence limits.

The ANOVA and subsequent statistical diagnostics were performed using the Stat Ease Design Expert v6.0.10 software.
A1.1 Data Statistical Analysis - Analysis of Variance (ANOVA) Technique

The analysis of the collected experimental data (shown in Chapter 5) used the Analysis of Variance (ANOVA) technique. ANOVA is used to determine whether the changes in the experiment variables or factors have caused the changes observed in the measured responses, or may have been caused by experimental error. In this way the ANOVA determined if each factor or variable caused a statistically significant change in the response using a 95% confidence limit throughout.

Analysis of variance has a number of core assumptions. The data is assumed to be modelled as the sum of a deterministic component and a random component. The random component accounts for the experimental error, which is assumed to follow a normal or Gaussian distribution about a mean and is referred to as the residual in ANOVA. The residual is therefore the difference between the values predicted by the developed model and the experimentally measured values. The deterministic or fixed component is assumed to be the sum of an overall mean and a contribution from each factor level that has a statistically significant effect on the response.

The designed experimental matrix (given in Chapter 5) is described as crossed since every level of each factor can be, but may not actually be, tested with every level of the other factors under investigation. This allows estimation of the affect of each factor (main effect) as well as any interaction between the factors, producing a model equation for two factors in the form Equation A1.1:

\[ y = m + a + b + (ab) + e \]  

Equation A1.1

where \( m \) = response mean, \( a \) = main effect of factor A, \( b \) = main effect of factor B, \( ab \) = interaction effect of factors A and B, and \( e \) = residual remaining between the measured and predicted data.
The estimation of model parameters is performed by calculation of the total variation within the response, the within level variation and across level variation for each factor using a technique known as value splitting. Value splitting breaks each response data point into its component parts (Equation A1.1). The mean response value at each factor level is first calculated. Subtracting the level mean from each data point then provides the residual value. The overall mean is calculated from all of the original data for the response. This grand mean is then subtracted from the individual level means to obtain the level effects.

The interaction effect is estimated by comparing the residuals at each level of factor A when factor B is changed. ANOVA analysis then compares these results with statistical confidence tables to provide an assessment of whether the effect is statistically significant within the predefined confidence limits. The confidence levels are generally determined by the experimenter and can be modified within data analysis programs such as StatEase Design Expert. A 95\% confidence level is used throughout this investigation. ANOVA uses the null hypothesis concept, which presumes changes in the factor levels and changes between factors, will not influence a measured response. The statistical confidence tests then indicate whether or not the null hypothesis can be rejected. Thus if a statistically significant result is indicated then one can be 95\% confident that the variation in measured response data is not due to random variation in the response.

**A1.2 Data Analysis Steps – Discharge Power Response Model Selection**

The first step of data analysis using the Design Expert software is the completion of the regression calculations to fit a polynomial model to the response, known as the sequential sum of squares in Design of Experiments processes. The program calculates the terms for all models that are not aliased and then statistically compares the models using a sum of squares or variance method and a lack of fit method. If a statistically significant model is identified within the pre-established
confidence limits then this model should be analysed further for the given response. These analyses will now be discussed further.

A1.2.1 Variance Comparison Analysis

Variance comparison begins with the sequential model sum of squares. This basically illustrates the accumulating improvement in the model fit to the experimental data as terms from higher order models are added. Each calculation is not the performed for the complete model; only the statistics for the additional terms are calculated. For instance, the significance of the linear terms is tested after removing the effect of the average. Then, the significance of the quadratic terms is tested after removing the average and linear effects (Design Expert, 2002). The ANOVA of the complete selected model is conducted later. The statistical significance of the additional terms is calculated using an F-test and the null hypothesis. The null hypothesis suggests additional terms should not improve the fit of the model to the experimental data within a pre-defined confidence limit. The F-value is calculated by comparing the variance between the model and experimental data with and without the new terms. The ratio of variances is then compared to tables of F-distribution data (Montgomery, 1997) and a probability value determined that the variance introduced by the new terms is statistically significant. The distributions and comparisons are completed within most DoE software packages.

The higher the F-value the more significant the terms are in improving the model and reducing the variance between the model and experimental data. The highest order polynomial where the additional terms are significant should be used for modelling the response. The sequential model sum of squares table for the pin electrode discharge power response is shown in Table A1.1. The F-values show that the terms added by the linear model are significant in reducing the variance between the model and experimental data, and thus improve the model. Adding further terms through the two-factor interaction (2FI) and the quadratic models does not
Appendix 1 - DoE Analysis of Pin Electrode Discharge Power Response

cause a statistically significant reduction in model to experimental data variation. These terms are not statistically significant using a 95% confidence criteria.

<table>
<thead>
<tr>
<th>Source</th>
<th>F-Value</th>
<th>Probability F-Value (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear</td>
<td>10.3437</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Two-factor interaction (2FI)</td>
<td>2.16342</td>
<td>9.29</td>
</tr>
<tr>
<td>Quadratic</td>
<td>1.20663</td>
<td>34.87</td>
</tr>
<tr>
<td>Cubic</td>
<td>0.86183</td>
<td>55.62</td>
</tr>
</tbody>
</table>

Table A1.1 - Sequential model sum of squares for the discharge power response computed using the Design Expert software

A1.2.2 Lack of Fit Analysis

The inclusion of replicate points within the experimental matrix allows the calculation of the pure experimental error and the estimation of the lack of fit for each model. Lack of fit compares the residual for a data point to the pure experimental error estimated from the replicated experimental points. If data point’s residual value is significantly larger than the pure experimental error this indicates that some element is likely to remain within the residuals that may be removed by a more appropriate model, thus the current model is unlikely to be accurate for prediction of the response. The F-test is again used to evaluate the hypothesis that useful information still remains within the residuals. A large probability F-value is desirable as it indicates that there is a statistically insignificant probability that there are still terms within the residuals that may be accounted for by a more suitable model.

The Lack of Fit for the discharge power response is calculated to be not significant. The linear model has a statistically insignificant lack of fit. Thus the residual remaining between the experimental data and the linear model can be accounted for by the experimental error. The model appears to include the terms required to predict the response to the accuracy with which the response can be measured.
A1.2.3 Model Selection Summary

The two separate model selection analyses used indicate the terms within the linear model are adequate to provide information with which the discharge power response can be predicted throughout the experimental space. The designed D-Optimal matrix was specified to provide experimental data that could be capable of modelling a second order or quadratic model if necessary. Since the actual model required to predict discharge power within the design space only contains linear terms, the number of experimental points within a D-Optimal design could have been reduced to 20 and the same model produced, but this could not have been predicted at the experiment design stage.

A1.3 ANOVA of Selected Discharge Power Response Model – Linear Model

The variance within the linear model is now analysed to assess how likely the selected model is to be in representing the response. The individual terms within the model are then analysed to assess if they are statistically significant.

The initial analysis calculates the model F-value by comparing the model variance with the pure error variance calculated from the replicate points. If the variances are of similar value, the ratio will be close to one and the combination of the tested factors cannot be said to have a significant effect on the response. This is not to say the factors do not affect the response, but that the combined effect cannot be distinguished from the experimental error. The probability of achieving the F-value if the null hypothesis is true is calculated. Thus a small probability F-value, below the specified confidence limit, calls for rejection of the null hypothesis, and therefore that the terms within the model have a significant effect on the response.

Once the statistical significance of the model has been analysed each of the terms within the model and their individual statistics are calculated. The mean square
values allow estimation of the variance of each term. The F-value then compares the term variance with the error variance. If the variances are similar, the term does not have a statistically significant affect on the response. The probability of the F value is again used to indicate the likelihood of achieving the calculated F value if the null hypothesis is true and there is no factor effect.

The Analysis of Variance for the discharge power response is shown in Table A1.2 below. From Table A1.2 the linear model is again shown to be statistically significant and also the model terms for the gas temperature and flowrate are statistically significant.

<table>
<thead>
<tr>
<th>Source</th>
<th>F Value</th>
<th>Probability &gt; F (%)</th>
<th>Implication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>10.34337</td>
<td>&lt; 0.0001</td>
<td>Significant</td>
</tr>
<tr>
<td>Temperature</td>
<td>30.53775</td>
<td>&lt; 0.0001</td>
<td>Significant</td>
</tr>
<tr>
<td>Gas Velocity</td>
<td>4.95681</td>
<td>3.52</td>
<td>Significant</td>
</tr>
<tr>
<td>Oxygen Concentration</td>
<td>0.05370</td>
<td>81.86</td>
<td></td>
</tr>
<tr>
<td>Water Vapour Concentration</td>
<td>2.47975</td>
<td>12.79</td>
<td></td>
</tr>
</tbody>
</table>

Table A1.2 – ANOVA table for the discharge power response using a pin electrode

The model terms of oxygen and water vapour concentration are statistically insignificant. The variation within the measured response when the oxygen or water vapour concentration factor levels were changed could not be distinguished from the pure experimental error. At this point of the analysis the model can be reduced by removal of the statistically insignificant terms from the analysis. Once the model had been reduced the ANOVA was recalculated and shown in Table A1.3.

<table>
<thead>
<tr>
<th>Source</th>
<th>F Value</th>
<th>Prob &gt; F (%)</th>
<th>Implication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>19.0874564</td>
<td>&lt; 0.0001</td>
<td>Significant</td>
</tr>
<tr>
<td>Temperature</td>
<td>31.8379550</td>
<td>&lt; 0.0001</td>
<td>Significant</td>
</tr>
<tr>
<td>Gas Velocity</td>
<td>5.0380165</td>
<td>3.32</td>
<td>Significant</td>
</tr>
</tbody>
</table>

Table A1.3 – ANOVA table for the discharge power response using a pin electrode following model reduction to remove the statistically insignificant terms of oxygen concentration and water vapour concentration
The Lack of Fit of the reduced model was recalculated. This ensured that the model was still adequate to predict the response within the experimental space and that no significant terms had been removed from the model. The Lack of Fit of the reduced model of the discharge power response was not statistically significant; thus the reduced model could still be used to predict the discharge power response through the design space investigated.

A1.3.1 Correlation Coefficient Comparison

Continuation of the ANOVA for the discharge power response assessed how closely the model followed the experimental data and therefore the amount of variability in the data that could be explained by the model. Correlation coefficients represented by various R-values provide measures of the difference between two sets of data, for example when comparing experimental data to the values predicted using a mathematical model of the process.

The R-value is the Pearson product moment correlation coefficient, \( R \), a dimensionless index that ranges from -1.0 to 1.0 inclusive and reflects the degree that a linear relationship exists between two data sets. The R-value is given by Equation A1.2. The square of the Pearson product moment correlation coefficient, or \( R^2 \) squared value, can be interpreted as the proportion of the variance in the model that is attributable to the variance in the experimental data.

\[
R = \frac{n(\sum XY) - (\sum X)(\sum Y)}{\sqrt{n\sum X^2 - (\sum X)^2}[n\sum Y^2 - (\sum Y)^2]}
\]

Equation A1.2

If two data sets show strong correlation (Figure A1.1(a)) then the \( R^2 \) value will be close to unity. If there is only a weak correlation (Figure A1.1 (b)) between the data sets then the \( R^2 \) value will be less than unity.
Appendix 1 - DoE Analysis of Pin Electrode Discharge Power Response

Figure A1.1– (a) Example of two data sets showing strong correlation ($R^2 = 0.98$) (b) Example of two data sets showing poor correlation ($R^2 = 0.73$)

The various R-Squared statistics should be as close to unity as possible to show that the calculated model accurately predicts the data collected during experimentation.
Appendix 1 - DoE Analysis of Pin Electrode Discharge Power Response

However, more importantly at this stage of analysis, the various R-Squared values should be separated by no more than 0.20 (StatEase Design Expert, 2002 and Collins, 2003). If a larger difference exists between these values then this tends to indicate that there is a problem with either the data or the model. The model and data require further interrogation to find Outliers (discussed further later in this Appendix) within the experimental data or investigation of a different order polynomial model.

The correlation coefficients including the R-Squared values for the reduced discharge power response model are shown in Table A1.4. The R-Squared value is a measure of the total variability around the mean that is explained by the model. However, the value will automatically increase as more terms are added to the model thus is limited in its usefulness. The Adjusted R-Squared is again a measure of the variability that is explained by the model, but adjusted for the number of terms in the model thus providing a better measure to compare different models. The Predicted R-Squared is a measure of how effective the model is at predicting the individual response values and is calculated using the predicted residual sum of squares or PRESS value. PRESS is essentially a measure of how the model fits each point in the design. The model terms are calculated without the first design point. This model is then used to calculate the residual for the first point. This procedure is conducted for each data point in turn and the squared residuals summed. As such the PRESS value for a model would be ideally zero, showing that all points are equally effective in determining the model and that the model accurately predicts the response values within the design space. The Predicted R-Squared and the Adjusted R-Squared shown in Table A1.4 are in close agreement, but the terms are only approximately 0.5 and the PRESS value is 7.2, both indicating that the model is not highly accurate in predicting actual values of the discharge power within the design space.

<table>
<thead>
<tr>
<th>Correlation Coefficient Table</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>R-Squared</td>
<td>0.58573</td>
</tr>
<tr>
<td>Adj R-Squared</td>
<td>0.55504</td>
</tr>
<tr>
<td>PRESS</td>
<td>7.22370</td>
</tr>
<tr>
<td>Pred R-Squared</td>
<td>0.49220</td>
</tr>
</tbody>
</table>
Appendix 1 - DoE Analysis of Pin Electrode Discharge Power Response

Table A1.4 - Correlation coefficients for the reduced model for the pin electrode discharge power response

The ANOVA also calculates the Adequate Precision statistic. This is essentially a signal to noise ratio comparing the range of predicted values at the design points to the average prediction error. Ratios greater than four are generally accepted to provide adequate model discrimination. The ratio calculated by the Design Expert software was 10.8, showing that there was an adequate signal to be easily distinguished and that the model could be used to navigate the design space to show how the discharge power varied as the flowrate and gas temperature changed.

In summary the R-Squared values showed that the model does not predict the actual experimental data values with great accuracy. However, the adequate signal to noise ratio shows that it does clearly demonstrate the trends within the discharge power response caused by changes to the flow velocity and gas temperature variables.

Finally the actual model terms were calculated. The reduced linear model developed through the regression analysis of the pin electrode discharge power experimental data is given by:

\[
\text{Power (W)} = 15.76 + 3.52 \times 10^{-3} T - 1.81 \times 10^{-4} V \quad \text{Equation A1.3}
\]

where \( T \) = gas temperature (K), \( V \) = gas flowrate (L.min\(^{-1}\) @ STP).

A1.3.2 Summary of Pin Electrode Discharge Power Response Model Selection

A model was produced which only included statistically significant terms. Initial analysis indicated the model could reasonably predict the trends within the pin electrode discharge power response caused by changes in gas temperature and gas
Appendix 1 – DoE Analysis of Pin Electrode Discharge Power Response

flowrate. However, the ANOVA process conducted on the experimental data along with developed model require further examination to ensure the underlying assumptions of the ANOVA were met and that there were no unusual data points or spurious trends.

A1.4 Discharge Power Response Model Diagnostics

A number of analysis procedures are available for examination of the experimental data to establish if the collected data is acceptable for model development. The analysis discussed above established that the equation could be used to model the measured data. The analysis discussed below was conducted to confirm the data on which the model was based was adequate and free from unusual values.

Analysis of the residual data for each experimental run allows identification of any time-based affects within the experimental data, such as changes in ambient conditions. The randomisation of the standard run order should cause the residual versus run plot to show a random pattern. Any trend evident within the graph would require investigation to find the source of the time-based affect. The residual against run number graph for the discharge power response is shown in Figure A1.2. The residuals were within the recommended boundaries throughout the experimental matrix. Thus there does not appear to have been any time-based effects that have significantly influenced the data and subsequent model. However there was a trend for the residuals to increase as the investigation progressed. The accuracy with which the model predicts the actual response value reduces for runs conducted later in the investigation. Such a trend may have been due to changes in some part of the experimental techniques over time or possibly due to some change in hardware such as sensor drift. However the trend did not cause the residuals between the predicted and actual data to grow beyond the statistically accepted limits (Design Expert, 2002).
Figure A1.2– Diagnostic plot of the pin electrode discharge power residual against run diagnostic plot

The Leverage is a term that assesses the quality of the experimental design in being able to develop a reliable model of the form identified by the earlier analysis. It provides an assessment of the potential of each design point to influence the selected model coefficients based on its position within the design space. No experimental design point should have leverage near unity as this indicates the data from this point dominates the developed model. All points should have near equal leverage, with no point having a leverage value greater than twice the average of the design. Any points with leverage near unity or a relatively high leverage compared to the other design points will be capable of exerting a large influence on the regression process and consequent model. This would result in any errors in the response measurement at these high leverage tests having a large influence on the model and thus making it less accurate in prediction of the actual response. Any high leverage design points should be replicated as this causes a reduction in the influence of any measurement errors during these tests.

The leverage values of the design points for the discharge power response investigation are shown in Figure A1.3. All design points had leverage values below
0.2 and all lay within twice the average value. Thus all of the design points had a similar capability to influence the developed discharge power response linear model.

![Figure A1.3 - Leverage of the design points for the pin electrode discharge power response investigation](image)

The Outlier T data initially appears similar to the residual versus run data graph (Figure A1.4). Outlier points are data points that appear unusual when analysed next to comparable points within the design space, assuming the chosen model is accurate. The model coefficients were calculated based on all of the design points except one. A prediction of the response at the removed point was then made and the residual evaluated.

The Outlier T statistic is the number of standard deviations between an actual data point and the predicted value at that point using a model based on all of the data except this point. An Outlier T value greater than 3.5 should be investigated to ensure the experimental data is reliable (Montgomery, 1997).
All of the data points measured during the discharge power investigation lay within the 3.5 limit (Figure A1.4), thus there were no unusual data points which tended to disagree with the trends indicated by the remaining data. Designed Experimental techniques do allow any data points that are believed to be erroneous to be removed from the experimental matrix and the remaining data re-analysed following the steps described above. However, before data is removed one must be confident that it is actually erroneous otherwise potentially useful data that indicates significant changes in trends or factor interactions is lost.

![Figure A1.4 - Outlier T for pin electrode discharge power experimental data](image)

The Cook's Distance diagnostic allows identification of points that are highly influential on the developed model. The Cook's Distance shows how the model coefficients calculated from the regression analysis would change if the individual points were removed from the data. The Cook's Distance is essentially a combination of the design point leverage and the Outlier T value of the measured data.
The Cook’s Distance for the discharge power response is shown in Figure A1.5, and demonstrates that none of the measured data points had a significantly larger effect on the developed model than any other.

![Figure A1.5 - Pin electrode discharge power Cook's Distance plot.](image)

**A1.4.1 Pin Electrode Discharge Power Model Diagnostic Summary**

The final diagnostic is simply a graph of the measured data against the predicted values at each design point. This provides a graphical assessment of how effective the model was at predicting the response data, and thus demonstrates the correlation coefficient ($R^2$) values discussed above. The discharge power measured data against the predicted data graph is shown in Figure A1.6 and demonstrates the relatively low accuracy with which the model predicted the discharge power response for the pin electrode.
The linear model could only predict the discharge power experimental data with an accuracy of 6.5%. However, Figure A1.6 shows that the model was capable of indicating the general trend with which the discharge power changed under the influence of the variable under investigation.

A1.5 Pin Electrode Discharge Power Response Data Analysis

Summary

The screening experiment discussed in detail above shows that the discharge power, when using a pin electrode, was influenced by the gas flow flowrate and the gas temperature. The oxygen and water vapour concentration did not affect the discharge power.

The Design Expert data analysis package was used to develop a regression model from the experimental data collected during the investigation to predict the discharge power under given conditions. The model was capable of predicting the
trends in the discharge power response, however detailed analysis including calculation of various correlation coefficients showed that the predicted values were not highly accurate when analysed alongside the measured data.

The experimental data was shown to be reliable through a number of diagnostic analyses, and supported the conclusions that the gas flow flowrate and the gas temperature were significant factors whilst the water vapour and oxygen concentrations of the gas could be eliminated from future investigation.
A2 DoE Analysis of Pin Electrode Regeneration Rate Response

The pin electrode regeneration rate response required analysis to assess the impact of the gas characteristics on filter regeneration caused by the Autoselective discharge. An ANOVA analysis, as performed on the discharge power response (Appendix A1), was used to assess the quality of the data and experimental process in providing conclusions of how the gas characteristics affected the regeneration rate. Each of the model diagnostics is discussed briefly in the following section to provide a full analysis of the experiment and data. However, for more detailed explanation of the relevance of each model diagnostic please refer to the pin electrode discharge power analysis in Appendix A1.

A2.1 Regeneration Rate Response Model Selection

The first analysis step was the sequential sum of squares to fit the various polynomial equations to the experimental data. The sequential sum of squares
identified at which point the additional model terms were not significant in improving the model using the specified confidence limits. The lack of fit test then identified which model reduced the residuals between the model and experimental data to the point where all useful terms were apparently included within the model. The two-factor interaction model was suggested from the sequential sum of squares and the model lack of fit tests performed within the Design Expert software for the regeneration rate response (Equation A2.1). This implied that the response surface model to predict the regeneration rate would be of the form:

\[ y = m + a + b + ab + e \]  
**Equation A2.1**

where \( m \) = response mean, \( a \) = main effect of factor A, \( b \) = main effect of factor B, \( ab \) = interaction effect of factors A and B, and \( e \) = residual remaining between the measured and predicted data.

Thus some or all of the terms within the two-factor interaction model were required to predict the regeneration rate response throughout the experimental space. The designed D-Optimal matrix was specified to provide the capability of modelling a second order or quadratic response surface if necessary. Examining the Experiment Design knowing that only a two-factor interaction model was required showed that a matrix of only 21 experiments would have been required to determine the same model.

**A2.1.1 Model Lack of Fit Analysis**

The Lack of Fit for the regeneration arte response is calculated and found to be not significant. The two-factor interaction model had a statistically insignificant lack of fit. Thus the residual remaining between the experimental data and the linear model could be accounted for by the experimental error. The model appeared to include the terms required to predict the response to the accuracy with which the response could be measured.
A2.2 ANOVA of the Selected Regeneration Rate Response Model

The two-factor interaction model was further analysed to assess its suitability for response prediction. The F-value for the model was calculated to assess if the variation within the model was comparable to the experimental error. The F-value showed that the model was statistically significant in predicting the regeneration rate response. The null hypothesis that the change in the response was not due to changes in the experimental factors was rejected. Changes to experimental factors investigated caused changes to the regeneration rate response.

The ANOVA of the full two-factor interaction model calculated which terms within the model were statistically significant. Most of the terms within the full two-factor interaction model were indicated to be insignificant by the calculated F-values probability. These showed that the variation caused by the particular model term could not be differentiated from experimental error, thus these terms were statistically insignificant. The only terms calculated to be statistically significant using a 95 % confidence limit were the gas temperature, the gas flowrate and the interaction between the temperature and flowrate (Table A2.1).

<table>
<thead>
<tr>
<th>Source</th>
<th>F Value</th>
<th>Prob &gt; F (%)</th>
<th>Implication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>59.41029338</td>
<td>&lt; 0.0001</td>
<td>Significant</td>
</tr>
<tr>
<td>A</td>
<td>98.58823268</td>
<td>&lt; 0.0001</td>
<td>Significant</td>
</tr>
<tr>
<td>B</td>
<td>60.49318405</td>
<td>&lt; 0.0001</td>
<td>Significant</td>
</tr>
<tr>
<td>AB</td>
<td>6.342462636</td>
<td>1.83</td>
<td>Significant</td>
</tr>
</tbody>
</table>

Table A2.1 - ANOVA table for the reduced two-factor interaction model for the regeneration rate response using a pin electrode

The lack of fit of the reduced two-factor interaction model was calculated to confirm that no significant terms were missing from the model to predict the response within
the experimental space. The lack of fit of the regeneration rate reduced model was insignificant and thus the model could be used to navigate the experimental space.

A2.2.1 Experimental and Model Data Correlation Coefficients

The correlation coefficients indicate how closely the reduced model predicted the response at the points tested within the design space. Values close to unity show that the two sets of values were in agreement. The various correlation coefficients were in agreement as to the accuracy of the model (Table A2.2), thus the model equation adequately predicted the measured data (Q&D Consulting Course Notes, 2003). The various R-squared values lay between 0.83 and 0.87 indicating the model could predict the regeneration rate at the various experimental points with a reasonable accuracy. The PRESS value of 0.017 also shows the model was accurate in predicting the response within the experimental space.

<table>
<thead>
<tr>
<th>Correlation Coefficient</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-Squared</td>
<td>0.873</td>
</tr>
<tr>
<td>Adj R-Squared</td>
<td>0.858</td>
</tr>
<tr>
<td>PRESS</td>
<td>0.017</td>
</tr>
<tr>
<td>Pred R-Squared</td>
<td>0.837</td>
</tr>
<tr>
<td>Adeq Precision</td>
<td>21.202</td>
</tr>
</tbody>
</table>

Table A2.2 - Correlation coefficients for the reduced regeneration rate model using a pin electrode

The Adequate Precision statistic, or signal to noise ratio, was 21.202 (Table A2.2) showing that the range in values of the predicted response was much larger than the error between the model and actual response data. The model residuals were much smaller than the range in regeneration rate values predicted throughout the design space and therefore the trends predicted by the data and model could be clearly distinguished.
Appendix 2 - DoE Analysis of Pin Electrode Regeneration Rate Response

The reduced model of the pin electrode regeneration rate is shown in Equation A2.2. The reduced two-factor interaction model was capable of predicting the actual response data within the design space with an accuracy of 6.5%.

\[(g/hr^{-1}) = 0.59 + 4.89 \times 10^{-4} T - 1.43 \times 10^{-5} V - 6.60 \times 10^{-8} TV \quad \text{Equation A2.2}\]

where \( T \) = gas temperature (K) and \( V \) = gas flow rate (l.min\(^{-1}\) @ STP)

**A2.3 Regeneration Rate Two-Factor Interaction (2FI) Model Diagnostics**

The experimental data and regression developed model data points were further analysed to identify unusual points or outliers and erroneous trends using the same process as utilised for the pin electrode discharge power.

The residuals versus run data allowed identification of any time-based effects that may have been introduced into the experimental results. The randomisation of the experimental run order should cause the residual against run graph to contain no discernable trends. Any spurious time-based effects would show as trends or patterns within this graph. Figure A2.1 shows that no such trends were evident within the regeneration rate response data. The residuals were within the recommended boundaries throughout the experimental matrix.
Figure A2.1 - Pin electrode regeneration rate response residuals versus run

The leverage value allows assessment of the quality of the experimental design by assessing the ability of each design point to affect the developed model coefficients. The leverage is based on the point's location within the design space and relative position to other points. All design points should have near equal leverage and no point should have leverage near unity. The regeneration rate leverage is shown in Figure A2.2. No design point had leverage more than double the average of the whole design and all points had leverage below 0.2. Thus all experimental design points had similar capability to influence the developed model of the regeneration rate achieved with a pin electrode.
Outliers are measured data points that appear unusual when analysed next to comparable points within the design space. Points which appear to be Outliers require further investigation to ensure the data is reliable as the response value does not fit with the trends indicated by the other data points. All of the regeneration rate response Outlier-T values were within acceptable limits (Design Expert, 2002) (Figure A2.3), thus all measured points were in reasonable agreement with the trends predicted by the rest of the data.
The Cook's Distance identifies the influence of each design point on the developed model due to the combination of the leverage and the measured response value. The Cook's Distance for each regeneration rate experimental point is shown in Figure A2.4. No experimental point had a significantly greater influence on the developed pin electrode regeneration rate model than any other.
Appendix 2 - DoE Analysis of Pin Electrode Regeneration Rate Response

Figure A2.4 – Cook’s Distance for pin electrode regeneration rate design points

A2.4 Pin Electrode Regeneration Rate Response Model

Summary

The pin electrode regeneration rate measured values against the values predicted by the model are shown in Figure A2.5. The values showed a reasonable correlation as indicated by the correlation coefficients discussed above.
The response surface screening investigation showed that the gas temperature and gas flowrate are significant in determining the regeneration rate achieved using a pin electrode configuration to generate the Autoselective discharge. The ANOVA also showed that there was an interaction between the gas temperature and the gas flowrate to determine the regeneration rate response. The effect of varying the gas flowrate was dependent upon whether the gas temperature is relatively high or low. The water vapour and oxygen concentration of the gas showed no statistically significant effect on the regeneration rate with the pin electrode glow discharge. The gas water vapour and oxygen concentration could be removed from future investigations as they had statistically negligible influence on the discharge power or the discharge’s performance in regenerating the filter.

A regression model of the regeneration rate response developed using the Design Expert software allowed prediction of the regeneration rate within the design space investigated. Analysis of the model, including calculation of correlation coefficients, indicated that the predicted values were in reasonable agreement with measured values.
A3 DoE Analysis for the Inserted Electrode Discharge Power Response

A3.1 Inserted Electrode Discharge Power Response Model Selection

The Design Expert software was used to conduct an Analysis of Variance (ANOVA) on the experimental data. The ANOVA technique determined whether the changes in the experimental factors had caused the changes observed in the measured responses. A brief outline of the analysis steps is provided in the following sections along with a brief discussion of the results. The results of the analyses, specifically the developed response surface model and its implications are discussed in greater detail in Chapter 6. A more detailed description of the key assumptions and steps involved in an ANOVA process is provided in Appendix A1 of this thesis.

The first step in the analysis was the sequential sum of squares that involved fitting various polynomial equations to the experimental data. This process identified the
Appendix A3 – Analysis of the Inserted Electrode Discharge Power Response Data

point at which additional model terms were not significant in improving the model within specified confidence limits. The lack of fit test was used to identify which equation minimised the residuals between the model and the experimental data. A linear response surface model (Equation A3.1) was indicated by the sequential sum of squares and the lack of fit tests to provide the most accurate prediction of the inserted electrode discharge power response throughout the design space. Some or all of the terms within the linear model were required to predict the discharge power response throughout the experimental space. The designed D-Optimal experimental matrix was specified to provide the capability to model a quadratic response surface if necessary. However, since only a linear model was necessary, a smaller experimental matrix could have provided the required data for model regression.

\[ y = a + b + c + e \quad \text{Equation A3.1} \]

where \( y \) is the system response (i.e. discharge power), \( a \) is the coefficient of factor \( A \), \( b \) the coefficient of factor \( B \), \( c \) the coefficient of factor \( C \) and \( e \) the residual.

A3.2 ANOVA of the Selected Response Model

The selected model was then analysed to investigate its suitability for response prediction. The F-value for the model was calculated to assess if the model was statistically significant in predicting the discharge power response (see Table A3.1), and shows that the null hypothesis should be rejected. Thus, the variation of the experimental factors within the ranges investigated did cause the response (discharge power) to change.

<table>
<thead>
<tr>
<th>Source</th>
<th>F Value</th>
<th>Probability &gt; F (%)</th>
<th>Implication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>12.02872</td>
<td>0.0004</td>
<td>Significant</td>
</tr>
<tr>
<td>Flowrate</td>
<td>6.11683</td>
<td>0.0268</td>
<td>Significant</td>
</tr>
<tr>
<td>Temperature</td>
<td>5.376603</td>
<td>0.0360</td>
<td>Significant</td>
</tr>
<tr>
<td>Loading</td>
<td>25.40021</td>
<td>0.0002</td>
<td>Significant</td>
</tr>
</tbody>
</table>
Table A3.1 – ANOVA table for the full linear model of the discharge power using an inserted electrode configuration

The continued ANOVA of the linear model terms showed that the gas temperature, the gas flowrate and the filter loading had statistically significant affects on the discharge power response. The lack of fit of the linear model was calculated to ensure that no significant terms were missing from the model to predict the response within the experimental space. The lack of fit of the reduced linear model was insignificant and thus this model could be used to describe the inserted electrode discharge power response within the experimental space.

The correlation coefficients (R-squared values) indicate how closely the regression model containing only significant terms predicts the response at those points actually tested within the experimental space. Values close to unity indicate that the two sets of data are in close agreement. The correlation coefficients for the discharge power response are shown in Table A3.2 below. The correlation coefficients lie between 0.93 and 0.97, indicating that the model predicts the discharge power at the various experimental points with good accuracy. The PRESS value of 0.99 also shows that the model is accurate within the design space. More detailed explanations of these ANOVA statistical terms are given in Appendix A1.

<table>
<thead>
<tr>
<th>Correlation Coefficient</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-Squared</td>
<td>0.720482</td>
</tr>
<tr>
<td>Adj R-Squared</td>
<td>0.660585</td>
</tr>
<tr>
<td>PRESS</td>
<td>4.299237</td>
</tr>
<tr>
<td>Pred R-Squared</td>
<td>0.532012</td>
</tr>
<tr>
<td>Adeq Precision</td>
<td>11.05317</td>
</tr>
</tbody>
</table>

Table A3.2 – Correlation coefficients for the inserted electrode discharge power reduced model

The signal to noise ratio calculated using the Adequate Precision statistic was 28.4 (see Table A3.2), demonstrating the range in values of predicted response was much larger than the error between the model and actual response data.
Therefore the reduced linear model was capable of accurately predicting the actual discharge power response data measured within the design space as the gas temperature, gas flowrate and filter loading were varied. The linear model of the inserted electrode discharge power is:

\[
\text{Power} = 9.121 - 2.172 \times 10^{-4} V + 1.612 \times 10^{-3} T + 0.576 L \quad \text{Equation A3.2}
\]

where \( T \) = gas temperature (K), \( V \) = gas flowrate (l.min\(^{-1}\) @ STP) and \( L \) = filter loading (g.l\(^{-1}\)).

The following section discusses the statistical diagnostics performed to confirm that the designed experiment and measured data were adequate to support the developed model.

**A3.3 Inserted Electrode Discharge Power Experimental Data and Model Diagnostics**

The experimental data gathered from the designed experimental matrix was analysed to identify unusual points, outliers and erroneous trends that would lead to an inaccurate model being developed.

The residuals versus run data allows identification of time-based effects that may have been introduced into the experimental results. The randomisation of the experimental run order should prevent the residual versus run graph from containing any trends. Figure A3.1 shows that no time based trends were apparent within the discharge power response data.
Figure A3.1 - Inserted electrode discharge power response versus run

The leverage indicates how each design point within an experiment is able to affect the developed model coefficients based on its location within the design space. Figure A3.2 shows that all design points had near equal leverage on the developed model and no point had a leverage value above 0.33. Therefore all experimental points had similar capability to influence the developed model of inserted electrode discharge power.
Appendix A3 – Analysis of the Inserted Electrode Discharge Power Response Data

Figure A3.2 – Experimental design leverage for the inserted electrode discharge power model

Outlier data points appear to be unusual when analysed next to comparable points within the design space. Outlier T values greater than 3.5 would require further investigation to ensure that data was reliable since the response value does not fit with the trends indicated by the other data points. All discharge power response Outlier T values are below the 3.5 threshold (see Figure A3.3). Therefore, no unusual data points are evident within the collected data.
The Cook's Distance diagnostic indicates the influence that each experimental design point had on the developed model due to both its leverage and the measured value. The Cook's Distance for all points within the experimental design from which the discharge power model was developed is shown in Figure A3.4. No experimental point had a significantly larger influence on the developed discharge power model than any other.
Finally the discharge power measured data points were compared to the points predicted using the regression model (see Figure A3.5). The comparison demonstrated the accuracy with which the model predicted the experimental values, and confirmed the accuracy indicated by the correlation coefficient statistics.
A3.4 *Inserted Electrode Discharge Power Response Statistical Analysis Summary*

The Analysis of Variance (ANOVA) of the data gathered using the D-Optimal designed experimental matrix showed that the inserted electrode discharge power response could be modelled using a linear equation containing terms for the gas temperature, gas flowrate and filter loading. The designed experiment and gathered data was analysed using statistical diagnostic techniques and found to be adequate to support the use of the model for predicting the discharge power response within the design space.

Analysis of the implications of the terms within the model along with discussion of the observed affects of the experimental variables on the inserted electrode discharge power is provided in Chapter 6 of this thesis.
A4 DoE Analysis for the Inserted Electrode Regeneration Rate Response

A4.1 Inserted Electrode Regeneration Rate Response Model Selection

The sequential sum of squares conducted by the StatEase Design Expert software v.6.0.10 identified the simplest polynomial equation that provided the best prediction of the regeneration rate experimental data within the set confidence limits. The lack of fit test then evaluates the residuals between the various polynomial models and the experimental data. These tests allowed selection of the lowest order polynomial that provided the closest prediction of the experimental data. Both the sum of squares and the lack of fit tests indicated that a linear model of the form shown in Equation A4.1 could be used to adequately predict the experimental data.

\[ y = a + b + c + e \quad \text{Equation A4.1} \]
where \( y \) is the system response (i.e. regeneration rate), \( a \) is the coefficient of factor A, \( b \) the coefficient of factor B, \( c \) the coefficient of factor C and \( e \) the residual.

Thus, some or all of the terms within a linear model were required to predict the regeneration rate response to changes in the gas conditions and filter loading.

The designed D-Optimal matrix (given in Chapter 6) was specified to provide the capability of modelling a second order or quadratic response surface if necessary. However, neither the inserted electrode discharge power (discussed in Appendix A3) or regeneration rate responses required a second order or quadratic model. As such a smaller experimental matrix could have been used to provide the data required for model development. Instead of the matrix of 18 experiments, a D-Optimal matrix of 12 experiments could have been conducted to provide the required data to develop the models. However, this would have required knowledge or prediction at the initial experiment design stage that a quadratic model was not necessary. If an experimental matrix for a linear model had been conducted and the developed linear model found to be inadequate, the additional points could not be simply added to the original matrix to provide the extra information. A complete new D-Optimal matrix suitable for quadratic model development would be required. Researchers in the DoE field indicate that the highest order model usually suitable for combustion and internal combustion engine processes is the quadratic model (Collins, 2003 and Montgomery 1996, p. 238), prompting its selection during initial experiment design.

A4.2 ANOVA of the Selected Response Model

The selected linear model is further analysed to assess the suitability for the response prediction. The Prob-F value for the model assesses if the variation in the response predicted by the model can be differentiated from the experimental error. The Prob-F value for the model (see Table A4.1) shows that it is statistically significant. The
null hypothesis that the change in response is not due to changes in the experimental factors is rejected. Changes in the levels of the experimental factors investigated cause changes in the regeneration rate response that can be differentiated from the experimental error.

<table>
<thead>
<tr>
<th>ANOVA for Inserted Electrode Regeneration Rate Response Surface Linear Model (All Model Terms Included)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source</td>
</tr>
<tr>
<td>Model</td>
</tr>
<tr>
<td>Flowrate</td>
</tr>
<tr>
<td>Temperature</td>
</tr>
<tr>
<td>Loading</td>
</tr>
</tbody>
</table>

Table A4.1 – ANOVA table for the regeneration rate linear response surface model

The ANOVA for the linear model terms calculates which terms are statistically significant. All terms within the linear model are shown to be statistically significant (see Table A4.1) using a 95% confidence limit. There is at least a 95% probability that the variation in response was due to the factor levels changing. Thus as the factor levels change from the low setting to the high setting the regeneration rate response was caused to change.

The correlation coefficients (R-squared values) were used to indicate how well the selected model predicted the response at those points tested within the design space. The various correlation coefficients were in close agreement (see Table A4.2) as to the accuracy of the model. The R-squared values lie between 0.97 and 0.985 demonstrating that the model can predict the regeneration rate with good accuracy. The very low PRESS value of 3.3E-4 also shows that the model is accurate in predicting the response at all the measured response points within the design space.
Table A4.2 - Correlation coefficients for the inserted electrode linear regeneration rate model

The signal to noise ratio or Adequate Precision statistic of 47 (see Table A4.2) indicates that the predicted response values fill a range that is much larger than the residual between the model and response data ['an Adequate Precision of 4 or greater is desired', (Design Expert, 2002)]. As such the changes in the predicted response caused by changes in the factor levels are significantly larger than the residual between the model and actual data. This showed that the model could be used to predict the response data as well as modelling the trends in the regeneration rate throughout the design space.

The linear response surface model for the inserted electrode regeneration rate is:

\[ g/hr^{-1} = 0.1403 - 2.708 \times 10^{-6}V + 6.015 \times 10^{-5}T + 0.0284L \]  

Equation A4.2

where \( T \) = gas temperature (K), \( V \) = gas flowrate (l.min\(^{-1}\) @ STP) and \( L \) = filter loading (g.l\(^{-1}\)).

The following section discusses the statistical diagnostics performed to confirm that the designed experiment and measured data were adequate to support the developed model.

A4.3  Inserted Electrode Regeneration Rate Experimental Data and Model Diagnostics

The designed experiment and measured data were analysed further to ensure that the data onto which the model was fitted was reliable and contained no outliers or apparently erroneous trends.
Appendix A4 - Analysis of the Inserted Electrode Regeneration Rate Data

The residuals versus run data identified any time based trends that may have influenced the measured data. The designed experimental matrix was randomised before being conducted prior to be conducted. This should cause the residual versus run data to be free from identifiable trends. Time based affects would appear as trends or patterns within the graph. Figure A4.1 shows that no time-based effects are apparent within the regeneration rate response.

![Figure A4.1 - Inserted electrode regeneration rate response versus run graph](image)

The leverage statistic shows how each design point was capable of affecting the model coefficients based on its position within the design space. All investigated design points had near equal leverage (see Figure A4.2) and thus all points had similar influence on the model.
Outliers are measured data points that are unusual when analysed next to comparable points within the design space. Data points with Outlier T values greater than 3.5 require further investigation to ensure the data is reliable and the trend that the response indicates is true. The regeneration rate measured response data Outlier T values were below 3.5 (see Figure A4.3). Thus all data point were in agreement with the trends indicated by the response at comparable points in the design space.
Figure A4.3 – Outlier T values of the inserted electrode regeneration rate response data

The Cook’s Distance evaluates the actual influence of each design point on the developed model based on a combination of its leverage and the measured response data. The Cook’s Distance of each regeneration rate experimental point is shown in Figure A4.4. No response data point had a notably larger influence on the developed inserted electrode regeneration rate model than any other.
Appendix A4 – Analysis of the Inserted Electrode Regeneration Rate Data

The inserted electrode regeneration rate measured values are compared to the predicted values in Figure A4.5. This demonstrates the accuracy with which the developed model predicts the measured data, and illustrates the accuracy indicated by the correlation coefficients discussed above.

Figure A4.4 - Cooks Distance of the inserted electrode regeneration rate response data
Figure A4.5 – Inserted electrode regeneration rate measured values against the values predicted by the developed linear model

A4.4 Inserted Electrode Regeneration Rate Data Analysis

Summary

The designed experiment discussed above showed that the gas temperature, the gas flow rate and the filter loading had statistically significant affects on the regeneration rate achieved by the inserted electrode. The analysis of the designed experiment and subsequently measured data showed that it was adequate to support these conclusions. From this data a linear model was developed using the Stat Ease Design Expert software, which was shown to accurately predict the response data at each experimental point investigated. Thus the model could be used to predict the regeneration rate achieved under the various gas and filter loading conditions within the design space.