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THE REGENERATION OF CERAMIC DIESEL EXHAUST FILTERS BY MEANS OF SURFACE PLASMA

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The Regeneration of Ceramic Diesel Exhaust Filters by Means of Surface Plasma

by

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ABSTRACT

The diesel engine is an energy-efficient power plant, but its exhaust emissions present a serious health and environmental problem. Drastic reductions of exhaust soot have been mandated throughout the world. Current control technologies, such as catalytic converters, alternative fuels, and advanced diesel engine combustion systems are only partially effective in controlling the soot generated from diesel engines. Exhaust filtration technology has to be deployed for effective soot control. Most of today's filter-based technologies, however, experience high operational back-pressures causing unfavorable fuel consumption. The key to the acceptability of barrier filters for diesel exhausts is the ability of the filter to be regenerated, or cleared of trapped particles, such that the exhaust back pressure remains low.

The use of ceramic filtration media for soot removal from combustion exhaust is well established. Since soot is combustible as carbon, most regeneration methods attempt to oxidize the soot to CO_2. The work reported here demonstrates the use of a One Atmosphere Uniform Glow Discharge Plasma (OAUGDP) to remove the deposited soot through oxidation by molecular radicals produced in the plasma. A ceramic filter containing electrodes that produce surface plasma when electrically energized was constructed and tested on the exhaust of a diesel engine. The filter removed soot particles from the diesel exhaust, and was subsequently subjected to periodic plasma exposures for soot removal. Experimental variables were flow rate, or engine rpm, and the frequency and duration of plasma application. The pressure drop across the filter and the number density of penetrating particles were continuously recorded during each test.

INTRODUCTION

The diesel engine is an energy-efficient power plant, but its exhaust emissions present a serious health and environmental problem. Diesel exhaust soot is identified as a Toxic Air Contaminant by the California Environmental Protection Agency. Drastic reductions of soot have been mandated throughout the world. Examples of stringent heavy-duty diesel emission standards include such regulations as the recently promulgated U.S. PM2.5, Euro-3, 4, 5, Japan 2000 and Korea 2000.

The damages caused by this fine particle matter are several. They include:

1. Physical damage, such as dirt on surfaces or corrosion of materials
2. Reduction of visibility
3. Health implications

Fine particles can escape the body's natural defense system and enter deep into the lungs. Once in the lungs, particles can cause several effects. Specific documented effects include increased incidence of asthma, chronic obstructive pulmonary disease, and pneumonia. The EPA estimates that cutting PM 2.5 pollution to the new recommended levels could save 20,000 lives each year particularly among the elderly with heart or lung conditions.

Current control technologies, such as catalytic converters, alternative fuels, and advanced diesel engine combustion systems are only partially effective in controlling soot. Diesel exhaust filtration technology has to be deployed for effective soot control. Most of today's filter-based technologies, however, experience high operational back-pressures causing unfavorable fuel consumption. Several of them, e.g. the catalyzed filters, have durability problems. Finally, many filter problems can be related to flaws in the filter regeneration systems.

The key to the acceptability of barrier filters for diesel exhausts is the ability of the filter to be regenerated, or cleared of trapped particles, such that the exhaust back pressure remains low. Since soot is combustible as carbon, most regeneration methods attempt to oxidize the soot to CO_2. The exhaust temperature at approximately 250°C is too low to allow spontaneous combustion (or oxidation) of the soot, but the gas may be heated to the combustion temperature of 550°C. Alternatively, a catalyst may be applied to the surface of the filter, promoting the oxidation of soot to CO_2 at normal operating temperature. Or, a catalyst may be added to the fuel itself, allowing the soot to burn out on the filter.

All of these regeneration methods have drawbacks. Heating the gas to 550°C is energy wasteful and creates a fire hazard around the vehicle exhaust system. Sulfur compounds can poison available catalysts, and the use of catalysts mandates very low sulfur fuels. In addition, catalyst additives to the fuel risks wear and/or deposit build-up on engine parts.

The investigation of plasma surface treatment started in the 1960s due to interest in computer technology, but it was found that many industrial processing technologies can benefit from the use of plasma surface cleaning[1]. Since then, intensive use of plasma surface treatment has developed in microelectronics, medical, textile, and other industries simply because there is no satisfactory alternate way to achieve the high quality results provided by plasma treatment[2].

Different samples react differently to plasma exposure. For metal surfaces, plasma treatment can strip off layers of surface oils and contaminants with thickness up to several microns. An example is given by Figure 1, which shows that soot on a steel surface has been removed by a corona discharge plasma. Plasma surface treatments allowed applications to cleaning and bonding to grow rapidly. The textile industry has been investigating plasma treatment to make fabrics wettable and to take dyes[3].

The One Atmosphere Uniform Glow Discharge Plasma (OAUGDP) is a recently developed and proprietary atmospheric glow discharge plasma, which can be operated at one atmosphere. The operation of this plasma requires only a RF power supply capable of providing a few tens of kV RMS at a few kilohertz, and no vacuum system. Characteristic areal power densities are a few tens to a few hundred milliwatts per square centimeter. The OAUGDP therefore does not have a power density high enough to damage or degrade most exposed materials, while providing an active species flux greater than corona discharges[4].

A power amplifier drives two electrodes capable of operating from 0 to 10 KV rms, with a frequency range from 1 kHz to 20 kHz. An optimum electrode gap spacing, rms voltage, and applied frequency result in the trapping of ions but not electrons between the two plates and produce the desired OAUGDP.

It has been demonstrated that the OAUGDP very effectively cleans surfaces of oxidizable, organic substances. Oxidation occurs because the plasma creates oxygenating radical molecules. Machine oil on metal surfaces can be completely removed after less than 10 minutes exposure to the OAUGDP, to the extent that a rust film appears on an iron surface minutes after removing the surface oil. The OAUGDP has been created on flat panels, and electrodes can be attached to a ceramic surface such that plasma can be generated adjacent to the surface.

The use of ceramic filtration media for soot removal from combustion exhaust is well established. A reliable method for removal of the captured soot from the ceramic surface (regeneration) is <u>not</u> available. The demonstration that plasma can be used to remove the deposited soot through oxidation is the objective of this work. Constructing a ceramic filter containing electrodes that produce surface plasma when electrically energized does this. The filter removes soot particles from a diesel exhaust, which are subsequently be subjected to periodic plasma exposures for soot removal.

FILTER DESIGN

A OAUGDP plasma can be generated at the surface of a dielectric, such as a ceramic filter, by placing grid electrodes on opposite sides of the dielectric and energizing these electrodes with an RF electrical supply, as shown in Figure 2. The plasma thus produced is seen as a sheet, covering the surface, as shown in Figure 3.

The application of the OAUGDP plasma to hydrocarbons, such as oils, has shown that approximately 5000 ¯ per min of hydrocarbon can be removed from surfaces. Based upon a typical diesel emission rate of 0.1 gm/m^3 and a packing density of 1 gm/cc, we find that the rate of carbon buildup on the filter would be 2000 per minute. Thus we see that the plasma is capable of oxidizing all of the carbon that the engine would produce.

Carbon burnoff tests were performed on a flat section of alumina ceramic, 2 mm thick. In this test, the charcoal from an artist's pencil was deposited on the alumina surface. Surface electrodes were energized to produce the OAUGDP plasma. Impedance matching was not used for these tests. It was found that approximately 1/3 of the charcoal could be removed after a 30 second exposure. The plasma could be generated in the vicinity of the wire electrodes, but did not extend uniformly over the entire ceramic surface. It was also found that the porous nature of the ceramic filter allowed sparks to penetrate, which damaged the ceramic. As a result, it was decided to use solid sheet electrodes, with a quartz barrier separation. The sheet electrodes will provide a uniform plasma over the entire ceramic surface, and the quartz barrier will prevent sparks. A diagram of this configuration is shown in Figure 4.

EXPERIMENTAL DESIGN

The test system as shown in Figure 5 was assembled. A 296 cc Yanmar diesel engine/generator set provides the exhaust. The pressure drop of the filter is continuously monitored by means of a transducer reporting to a data logger. The outlet particle concentration and size distribution are continuously monitored by means of an optical particle counter. Figure 6 shows the filter assembly with inlet and outlet test ports.

The principal independent variables in this program are engine speed (exhaust flow rate), cleaning frequency and cleaning duration. All parameters directly affect pressure drop and capture efficiency, which are the dependent variables. The test program is arranged to identify the effect of each independent variable. The pressure drop across the filter and the number density of penetrating particles are continuously recorded during each test. An initial test without the filter would be run to characterize the engine exhaust. Finally, a long-term test using the best combination of face velocity and cleaning frequency will be carried out in order to demonstrate stable long-term performance.

The flow resistance of the filter will be approximately 2 bar per meter per second face velocity. An allowable back pressure of 0.1 bar yields a face velocity of 0.05 m/sec. The face area of the filter is 0.044 m^2, which yields a flow volume of 0.0022 m^3/sec. The flow rate is thus varied around this value. The cleaning frequency is varied from continuous plasma application to once every four hours. The duration of plasma application is varied from 5 to 30 minutes.

RESULTS/CONCLUSIONS

A plasma is generated in the gap between the ceramic filter and the quartz tube at an applied voltage of 8 kVrms and a frequency of 4 kHz. The power needed to maintain the discharge is 500 watts. The parametric test program will be carried out in April, 2000. The principal dependent variable will be the filter pressure drop. The pressure drop will increase as soot is deposited on the filter. Periodic application of the plasma will oxidize the collected soot and restore the pressure drop to a lower value. A plot of pressure drop versus time will thus be a sawtooth. A successful result will be one in which periodic application of the plasma will stabilize the sawtooth maximum and minimum, allowing continuous operation.

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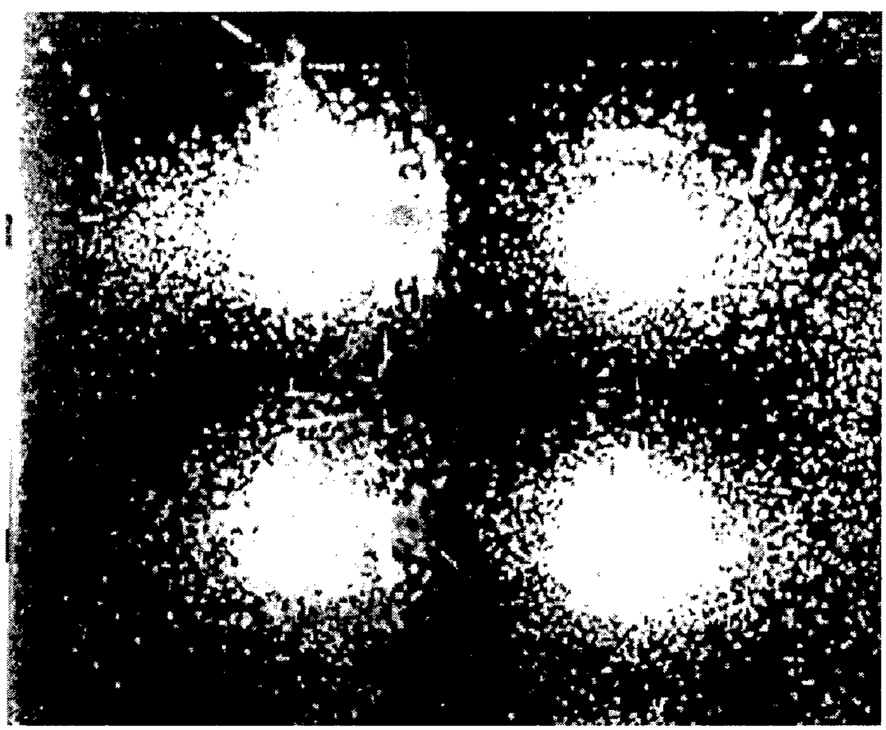

Figure 1. Oxidation of Soot by Means of Corona Discharge

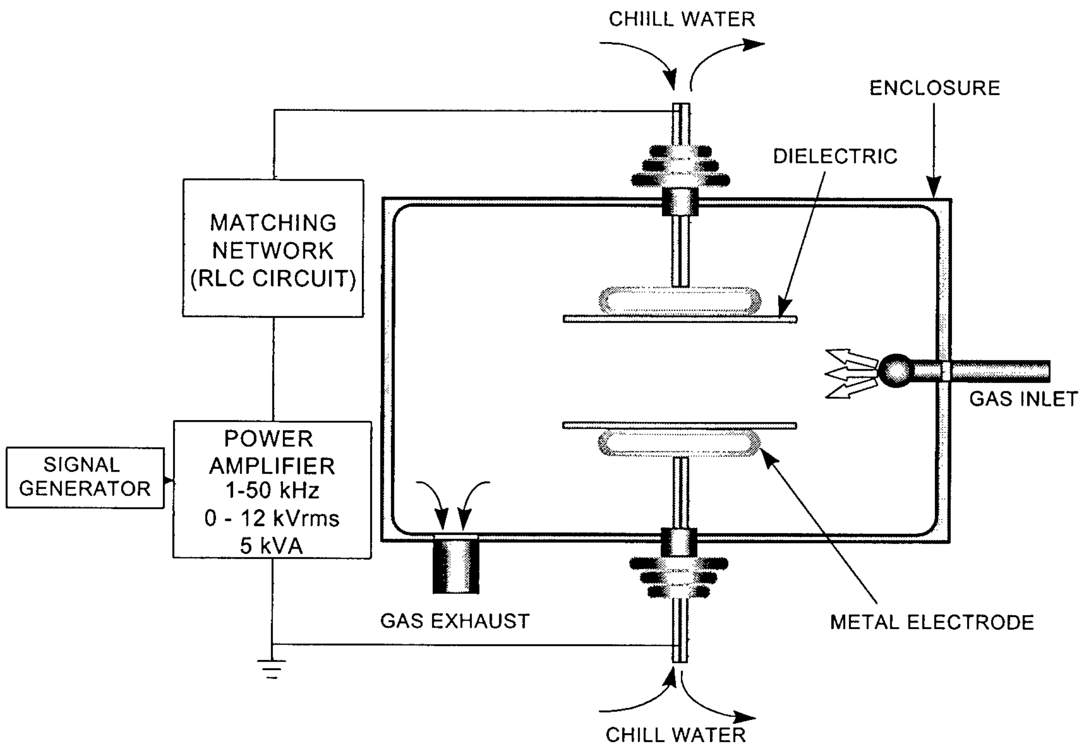

Figure 2. OAUGDP Plasma Generation

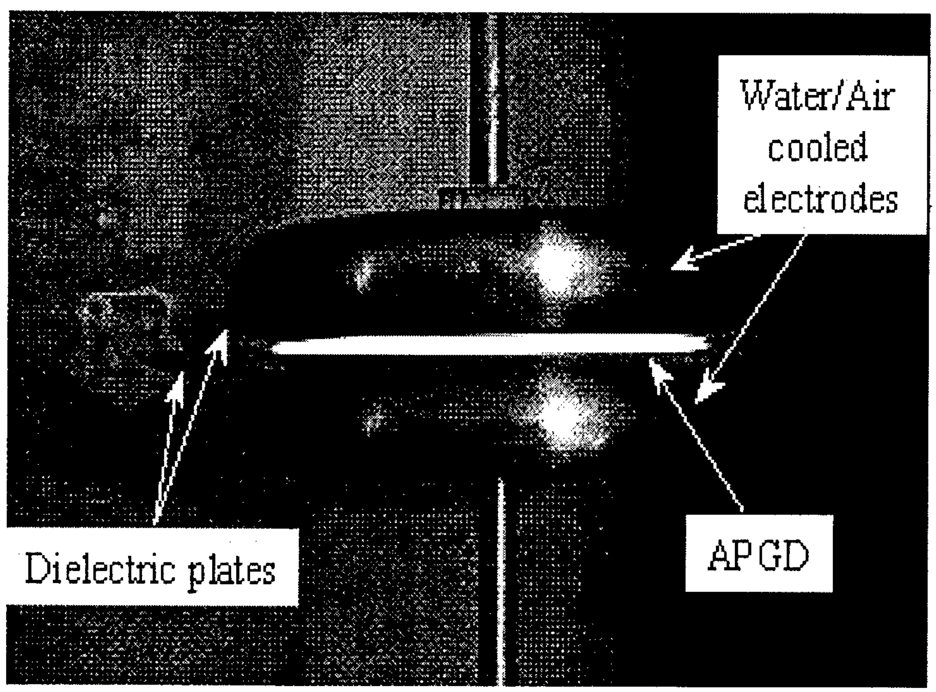

Figure 3. OAUGDP Plasma Appearance

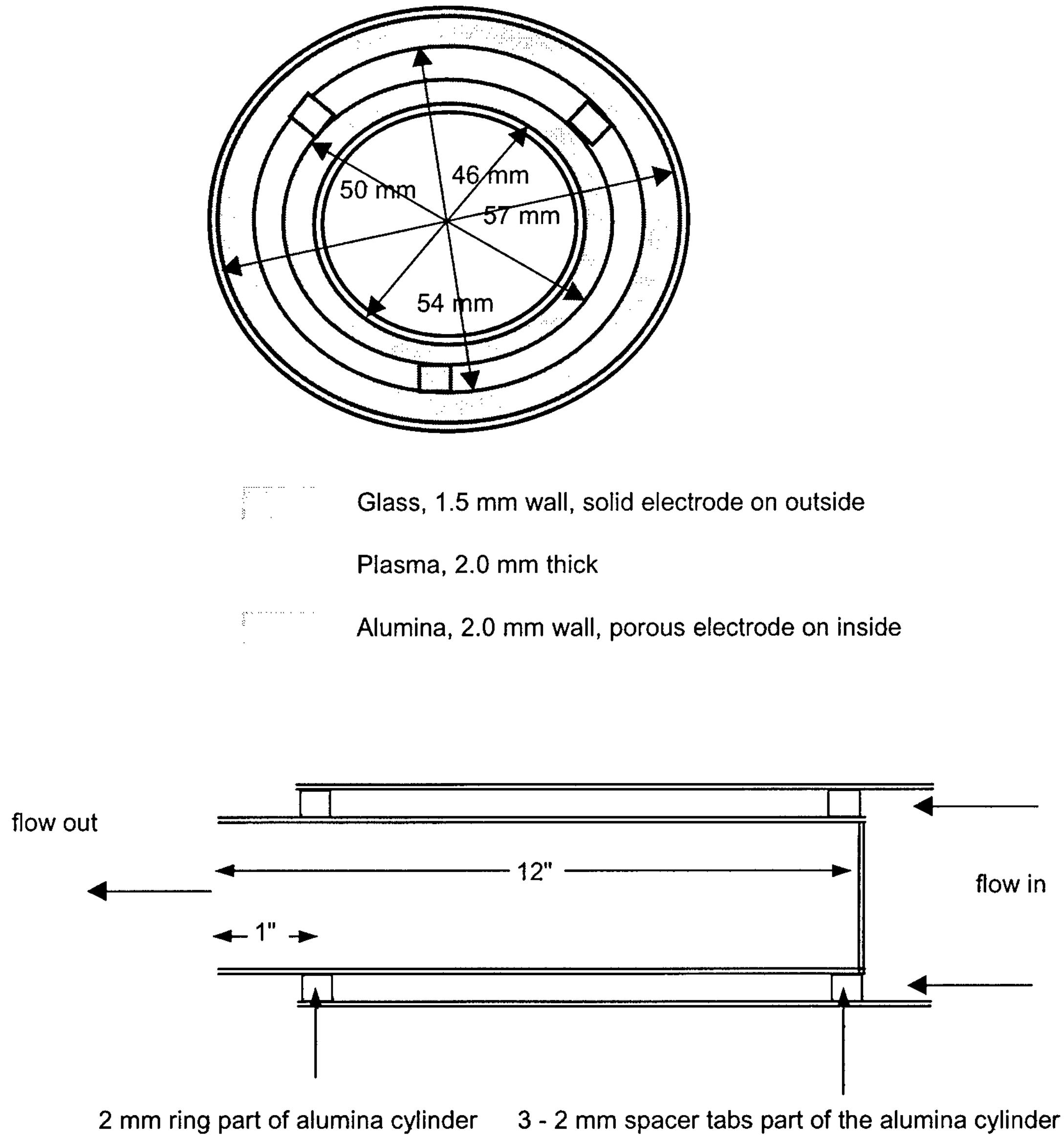

Figure 4. The Filter/Plasma Arrangement

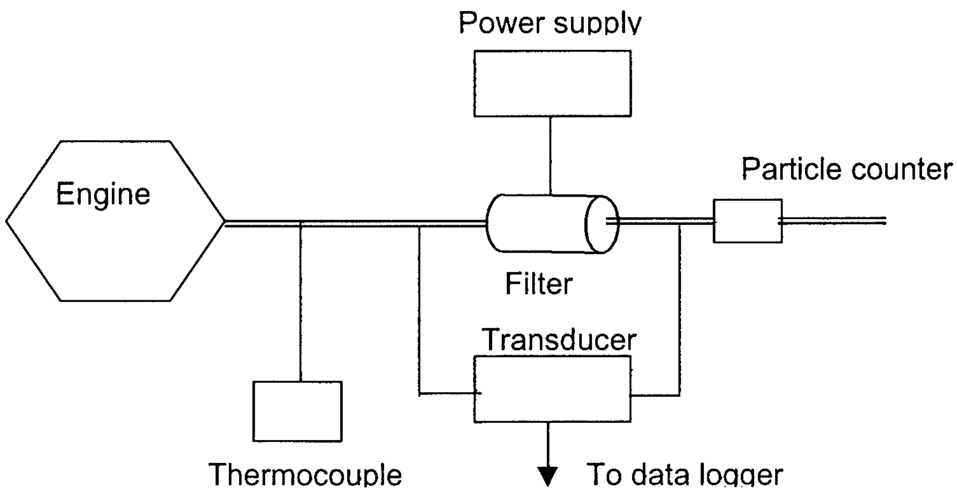

Figure 5. Experimental Arrangement

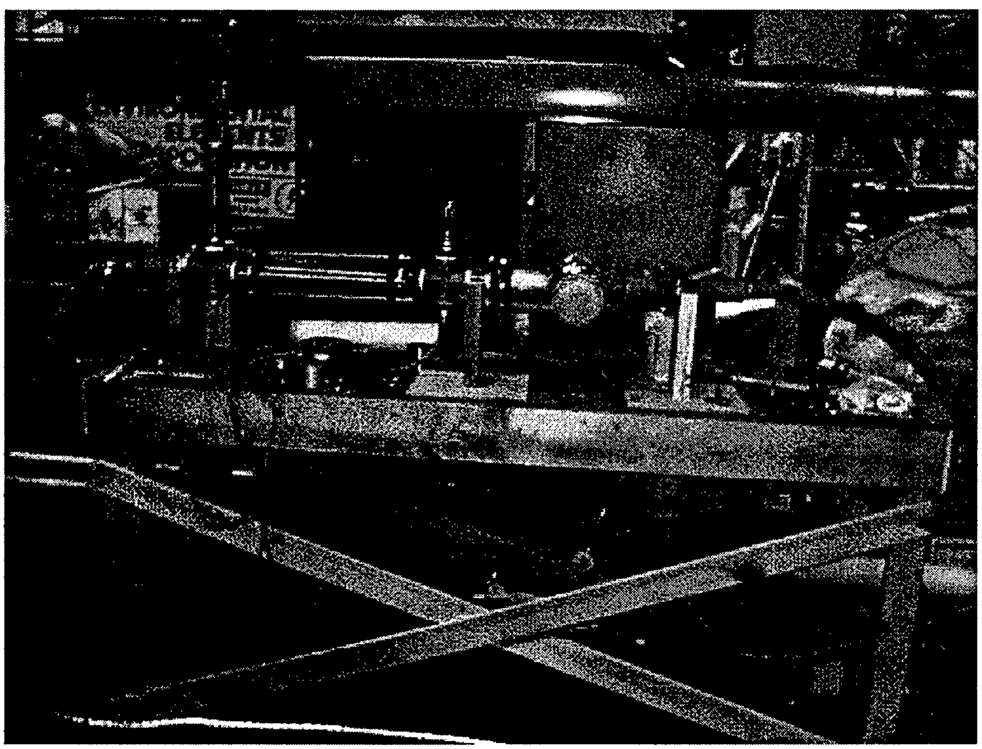

Figure 6. The Filter Assembly