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**DIRECT-ENERGY-REGENERATED
PARTICULATE TRAP TECHNOLOGY**

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EXECUTIVE SUMMARY

The objective of this CRADA between Lockheed Martin and Cummins Engine Company was to develop fiber-reinforced silicon carbide (SiC) composite materials for use as diesel engine particulate traps. Chemical vapor deposition techniques were used to partially densify and rigidize a thin fibrous substrate and produce the porous SiC-based filter. Microwave energy was used to directly couple to the deposited SiC to uniformly heat the filter and oxidize the collected carbon particulates. For commercial usage particulate traps must: 1) filter carbon particulates from a high temperature diesel exhaust at an acceptably low backpressure, 2) survive thousands of thermal transients due to regeneration or cleaning of the filter by oxidizing the collected carbon, 3) be durable and reliable over the expected life of the filter (300,000 miles or 10,000 hours), and 4) provide a low overall operating cost which is competitive with other filtering techniques.

The development efforts performed as part of this CRADA have resulted in a very promising new technology for Cummins Engine Company. Ceramic fiber based filter papers were developed at Fleetguard, Inc., (a Cummins Subsidiary) and used to produce the spiral wound, corrugated filter cartridges. Optimized SiC coatings were developed at Lockheed Martin which couple with 2.45 GHz microwaves. Prototype particulate filter cartridges fabricated at Fleetguard and rigidized at Lockheed Martin performed well in single cylinder engine tests at Cummins. These prototype filters obtained filtering efficiencies greater than 80% at acceptably low backpressures and could be successfully headed and regenerated using a conventional in-home microwave oven.

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DIRECT-ENERGY-REGENERATED PARTICULATE TRAP TECHNOLOGY

ABSTRACT

Prototype particulate filters were fabricated from ceramic fiber based filter papers using a spiral wound-corrugated filter structure. These ceramic filters were coated with a silicon carbide coating that coupled with 2.45 GHz microwaves. Coated filters were enclosed in stainless steel housings for engine evaluation. Engine backpressure reduction was observed after using microwave energy to heat the filter to carbon ignition temperatures.

Considerable effort remains to engineer the filter, develop the filter regeneration strategy, and develop the electronics to yield a reliable and durable filter system. Research is continuing to understand the performance of the filter under a range of engine operating conditions and methods to increase the robustness of the particulate filter system.

INTRODUCTION

Diesel engines are a prime mover of freight in the United States. Essentially 100% of the heavy duty engines used in class 8 trucks are powered by diesel engines due to their efficiency and cost effectiveness compared to competing propulsion systems. Because of legislated reductions in diesel engine emissions, considerable research has been focused on the reduction of these emissions while maintaining the durability, reliability, and fuel economy of diesel engines.

The Environmental Protection Agency (EPA) has determined that particulate from diesel powered vehicles represent a potential health hazard. As a result, regulations have been promulgated limiting the allowable amounts of particulate from those vehicles. The 0.1 g/bhp-hr particulate standard that applies to heavy-duty diesels became effective in 1994.

Engine manufacturers have met those requirements through the use of engine modifications and/or oxidation catalysts. EPA has established more stringent standards for diesel-powered urban buses because of health concerns in densely populated urban areas.

Particulate traps have been shown to significantly reduce carbon particulate emissions from diesel engines. However, current particulate trap systems are expensive and unreliable. Demonstration of a fiber based particulate trap coupled with a novel microwave energy regeneration system which address reliability and cost issues would greatly accelerate the introduction of this filtration technology into diesel engines.

FILTER DEVELOPMENT

Filtration of airborne particulate is accomplished by a number of mechanisms. The two dominant means are particle interception and diffusion. Particle interception occurs when the contaminant size is larger than the pores in a filter media which traps the contaminant. The dominant mechanism which affects the efficiency of an air filter is particle diffusion. Particle diffusion is best described by understanding that the path of an individual particle is random and does not follow streamline flow. The path of the particle is then much more likely to intersect the filter structure. When a particle intersects a fiber it is likely to remain trapped on the fiber surface. For example, the home furnace filter is effective in removing pollens and dust in the 10 to 100 micron range even though the spacing in the filter is considerably greater.

An exhaust filter or diesel particulate trap must be designed to remove particles or soot on the order of 0.1 to 1.0 micron in size. Experience with fiber based filter media has shown that

fiber based systems are more effective than porous structures such as membranes or ceramic monoliths in terms of the efficiency and particulate capacity.

A microglass filter was used as a 'surrogate' filter element to examine the effects of a fiber filter on trapping efficiency and engine restriction. Microglass is available in a range of fiber diameters and material was chosen that was similar to the commercially available alumina and other ceramic fibers proposed for the particulate filter. Of course, the fiber and binder materials in this surrogate filter were not suitable for the high temperature regeneration.

Selection of a suitable microglass 'surrogate' media was based upon filtration efficiency and restriction. DOP(Di-Octyl Phthalate) smoke, a fine 0.3 micron particle, is commonly used for testing HEPA and ULPA air filters and the particulate size is very close to that of exhaust soot. DOP smoke was used to estimate the efficiency expected in the particulate trap where a target range of 60-80% particulate removal had been established.

The air resistance can be used to calculate the restriction of an ideal filter element at various flows. At the rated horsepower the exhaust flow for the B5.9 liter engine is roughly 400 SCFM or 11.3 CMM. An estimate of 0.5 kPa back pressure was calculated for a filter of two square meters. This corresponds to the area that might be packaged in a cylindrical 15 by 15 cm element with a spiral wound design. Filters were then fabricated using two square meters of media in a radial pleated element for testing. The annular elements were 23 cm outside diameter by 15 cm inside diameter and 24 cm in height. The media was supported on both sides by wire screen and consisted of 125, 3.5 cm pleats. This provided an effective area of 2 square meters for the 'surrogate' samples. When tested at 11.3 CMM the restriction of these elements were 0.7 kPa which is close to the 0.5 kPa estimate.

Filter samples and a housing were tested on a single cylinder L10 (SCE L10) engine which was modified to produce particulate at a high rate, 2 g/bhp-hr or 32.5 grams per hour. While

the displacement of the SCE L10 is about 30% of the B5.9 which is a target engine, the particulate generation rate was very close to the 0.2 g/bhp-hr of a 160 bhp B5.9.

The trapping efficiency and back pressure is shown in Figure 1.

Figure 1. Efficiency and Pressure Drop versus Time for a Microglass Filter.

As expected the initial restriction was very low. Restriction after 7 hours was about 25 kPa which has been targeted as the maximum allowable restriction before regeneration. It is expected that the restriction would rise more quickly on a larger engine with higher flow, but the result was encouraging. With the same loading and a three fold increase in flow, the regeneration interval could still be assumed to be greater than two hours. The efficiency began at better than 80%, dropped, then rose to a high of 90% and declined to about 60% after seven hours. The decrease in efficiency was attributed to a leakage at the filter endplates. The test does suggest that the original estimate of 60 to 80% efficiency was reasonable.

The results of the SCE L10 tests were encouraging and indicate that assumptions about filter performance were reasonable. The physical properties of a filter media to achieve

the required performance in an exhaust particulate trap were confirmed during these tests. These physical parameters directed the development of a ceramic paper to be used with chemical vapor infiltration for a regenerable element.

Alumina fiber(ICI Saffil) was chosen to produce filter media for the diesel particulate filter. Information on the properties of silicon carbide coated alumina and its resistance to hot gas environments is known. This composite has demonstrated excellent heating in a microwave. However, unlike the microglass fibers, Saffil is available in a narrow range of products with an average fiber diameter of roughly 3 microns. When the work began to duplicate the properties of the microglass paper with alumina fiber, many fiber samples were not suitable because of the short fiber length. The best results obtained were working with an unmilled bulk version of fiber designated Saffil RF.

Formulation work was accomplished by making small (30.4 cm by 30.4 cm) samples cast in a laboratory hand sheet mold. A fiber formulation was dispersed in water and then drained rapidly through a forming fabric or screen. The wet hand sheet was then blotted to remove excess water and dried on a hot surface. Additional difficulties with Saffil fiber were encountered at this point. Saffil is very weak in both wet web and dry strength and on its own has very high air resistance. In order to increase the permeability of Saffil fiber and add strength, other 'fugitive' fibers were required. Various binder fibers which are highly fibrillated and provide strength through entanglement in the web have been examined. Chemical resins to aid formation and wet strength were also tested. In order for the paper samples to have good 'fired' strength a thermosetting phenolic coating was added to maintain geometry during chemical vapor infiltration (CVI). The unknown affect of the coating on permeability and pore structure raised concerns during the design process.

Candidate samples coated at Oak Ridge National Laboratory received a 1 to 2 micron CVI coating of silicon carbide. It was

determined that the coating did not significantly alter the porosity or pore structure of the media. Roughly 20-25% fugitive materials were incorporated to add strength and improve the porosity of the media. The CVI coating effectively replaced the fugitive material producing samples with characteristics similar to the original paper.

Pilot paper machine trials have been conducted on a laboratory machine capable of making continuous Saffil paper. The goal was to produce sufficient amounts of Saffil papers for building filter prototypes. Additions were incorporated with the Saffil fiber to develop the green strength and porosity required for the particulate filter application.

Packaging density of the filter media is a primary concern since the filter must reside within a microwave cavity. The basic filter shape is a cylinder 15.2 cm in diameter and 15.2 cm in length. The construction considered is that of a single face corrugated or pleated media to be spiral wound, Figure 2. This geometry requires the ceramic paper be either formed into a sinusoidal or pleated arrangement and then alternately sealed between flat layers of material as it is wound.

Figure 2. Filter Dimensions and Geometry

Media properties will affect the ability to produce an element of ideal geometry. The

samples, fabricated by Fleetguard, have used the pleated design with triangular cells of approximately 6 mm on each side and a material thickness of 1.6 mm. The estimated area is 1 square meter. Work is underway to improve the base paper, making it thinner and allowing for smaller pleats or possible fluting. This will give an increase in the packing density of 2 to 3 fold. The immediate goal is to reach the original target of 2 square meters with 1 mm thick media and a 3 mm pleat.

With the pleated or corrugated configuration, it is necessary to seal the alternating ends of the cells to create a flow path as shown in Figure 3. Ideally, one edge would be sealed as the pleated and flat sheets are combined and then the opposing end sealed as the element is wound. This requires a sealant that will withstand the chemical vapor processing without opening up the flow path. A sealant composed of milled Saffil, vinyl acetate and powdered phenolic resin has been tested with some success.

Figure 3. Gas Flow Through Filter Media.

The samples fabricated from the pilot machine trials have been submitted to both Oak Ridge National Laboratory and Composite Innovations Corporation. The prototypes to ORNL were somewhat smaller in diameter due to the furnace size limitations. The samples coated by Composite Innovations Corporation were full size. The weight of the full size filter prior to infiltration was approximately 300 grams with sealant. Due to the weight loss of fugitive material in both the media and sealant the

finished weight was also approximately 300 grams.

The element mass is much lower than the extruded ceramic traps currently available and provides more rapid heating. The elements are also resilient although not extremely strong at this point in the development. As completed filters of better geometry become available, strength and durability testing will commence. A Composite Innovations Corporation coated filter is shown in Figure 4.

Figure 4. SiC Coated Alumina Fiber Filter

MICROWAVE HEATING

Several filter prototypes were provided to FM Technologies, Inc. for heating experiments using the cylindrical applicator design. A 2.45 GHz microwave source was used in these experiments. The microwave energy was directed to the applicator using WR284 waveguide and the incident and reflected power were monitored during heating. Thermocouples were placed inside the filter at three positions along the axis of the cylinder to obtain a measure of the axial temperature profile. These thermocouples were inserted through small holes drilled in the cavity wall, thermal insulation, and the filter in such a manner that the thermocouples could be moved in and out to determine the radial temperature profile as well. Figure 5 shows the positions of the thermocouples and shows the heating data near the top and center of the

filter. The filter was heated to regeneration temperature in less than 5 minutes with only 750 Watts of input microwave power. However, the axial temperature gradient between T1 and T3 exceeded 200 °C.

The radial temperature gradient was similar in magnitude to the axial gradient. In order to minimize the thermal gradient, a proprietary microwave feed system was developed. The heating results using this system, with 750 Watts of input power, are presented in Figure 6.

Figure 5. Microwave Heating Showing Large Thermal Gradient.

Figure 6. Improved Thermal Gradient.

The thermocouple locations were the same as indicated previously, but data from all four thermocouples are presented. The heating rate is reduced slightly, but the uniformity of heating is now excellent, with an axial and radial variation of approximately 100°C.

The data shown in Figures 5 and 6 and were obtained in FMT's laboratory using a microwave applicator that was fabricated from a 17.5 cm outer diameter brass tube. The microwave applicator ends were removable perforated brass plates. The end plates were removed, the prototype filter was wrapped in a blanket of high temperature alumina insulation, which was inserted into the tube, and then the end plates were reattached.

SYSTEM EVALUATION

In order to allow testing of the microwave regeneration method with a carbon-loaded filter under engine conditions in a test cell at the Cummins Technical Center, the filter was put into a stainless steel "can" following current exhaust system practices in the diesel engine industry.

The canned prototype filter was returned to FMT, and a microwave feed system was installed. The canned filter was heated with FMT's microwave system, which supplied one kilowatt of electrical power to the magnetron.

To validate laboratory results a proof of concept evaluation was planned for the microwave filter system, Figure 7. The primary objective of the evaluation was to determine if a microwave filter could in fact oxidize particulate (regenerate) from a diesel engine. Two distinct evaluations were conducted to assess the regeneration capability of the microwave system. The first evaluation assessed regeneration capabilities without exhaust flow. The engine was operated for ten hours at 1500 rpm producing 17.2 kW. During this period engine back pressure was monitored but not recorded. At the end of the loading period the engine was switched off and power to magnetron was engaged. The absence of exhaust flow required the injection of air to provide sufficient oxygen to oxidize carbon.

The second evaluation measured the systems ability to regenerate while the engine continued to operate. Once the back pressure doubled, engine operation was set to idle (800 RPM) and power to the magnetron was engaged.

Two methods used to detect regeneration include 1) temperature and 2) exhaust manifold back pressure. Thermocouples inserted into the

Figure 7. Test Cell Evaluation of Microwave Filter

bed of the filter recorded temperature spikes which could indicate regeneration. Although temperature measurements provide adequate detection capabilities, back pressure measurements provide more useful information. Back pressure readings can signal when to start the regeneration process and the effectiveness of the process. Traditionally Cummins has initiated regeneration once the back pressure doubles its starting value at the same operating condition. The 2x rule allows collection of sufficient particulates to produce a measurable event without melting the filter because of the extreme exotherms associated with carbon oxidation.

Testing without exhaust flow demonstrated that it was possible to heat a filter system to the temperatures necessary for regeneration by microwaves. Time and temperature history of the three thermocouples, Figure 8, show the center region achieved temperatures necessary to oxidize carbon. The temperature fluctuations during the first one thousand seconds reflect system integrity evaluation and leak check using partial power. After applying full magnetron power, temperatures increase rapidly to 600°C and began leveling, an indication of insufficient oxygen. Terminating the exhaust flow also decreased air supply to the filter. An injection of ambient air into the system resulted in a temperature spike to 760°C; the sudden increase suggest carbon oxidation. A second injection resulted in cooler temperatures suggesting completion of the reaction. Results obtained attempting to regenerate in the presence of exhaust flow proved very positive.

Figure 8. Magnetron Power Turned on at 1000 Seconds.

Figure 9 details the time history of both temperature and engine back pressure readings. Prior to dropping the engine to low idle the back pressure measured 18 kPa and temperature readings exceeded 425°C. Cooler exhaust temperatures, associated with idling, slightly decreased filter temperatures. However, within seconds of switching on the microwave power, temperature of the center

region increased very rapidly to 760°C, the inlet and outlet temperatures increased slightly. Twenty five seconds after peaking at 760°C the center temperature decreased and all temperatures converged to 425°C, the same as before the temperature spike. A review of exhaust back pressure results indicates a 50% decrease occurred after the temperature spike.

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Figure 9. Temperature Increase Observed at Idle with Magnetron Power.

SUMMARY

A composite particulate filter was developed which was heated using microwave energy. Temperature measurements indicate that the temperatures achieved were sufficient to oxidize diesel particulate without exhaust flow. Back pressure and temperature data strongly suggest the occurrence of regeneration during a low idle operation. A key concern is the detection of the regeneration event. Back pressure and to a lesser degree temperature readings are indicators of the regeneration event. However, localized heating in the filter may go undetected. Improved methods of detecting regeneration of the filter are required for development purposes.

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