Development of A Microwave Assisted Particulate Filter Regeneration System

Matthew Henrichsen and Sriram Popuri, Cummins Inc.,

Abstract

The need for active regeneration of diesel particulate filters and the advantages of microwave assisted regeneration are discussed. The current study has multiple objectives, which include developing a microwave assisted particulate filter regeneration system for future generation light-duty diesel applications, including PNGV type applications. A variable power 2.0 kW microwave system and a tuned waveguide were employed. Cavity geometry is being optimized with the aid of computational modeling and temperature measurements during microwave heating. A wall-flow ceramic-fiber filter (6″×6″) with superior thermal shock resistance, high filtration efficiency, and high soot capacity was used. The microwave assisted particulate filter regeneration system has operated for more than 100 hours in an engine test-cell with a 5.9-liter diesel engine with automated split exhaust flow and by-pass flow capabilities. Filter regeneration was demonstrated using soot loads up to 10 g/liter and engine exhaust at idling flow rates as the oxygen source. A parametric study to determine the optimal combination of soot loading, oxidant flow rate, microwave power and heating time is underway. Preliminary experimental results are reported.

Introduction

Diesel particulate matter (DPM) emissions regulations have become increasingly stringent in recent years. On-highway heavy-duty engines sold in the US for the 2007 model year will be required to emit less than 0.01 g/bhp·hr. This is less than 2% of the 1988 DPM standard for heavy-duty engines (Figure 1). It is likely that diesel particulate filters, which remove the solid fraction (soot) of diesel particulate from the exhaust, will be necessary to meet the 2007 PM standard.

Filters capable of removing more than 90% of the soot are currently available.

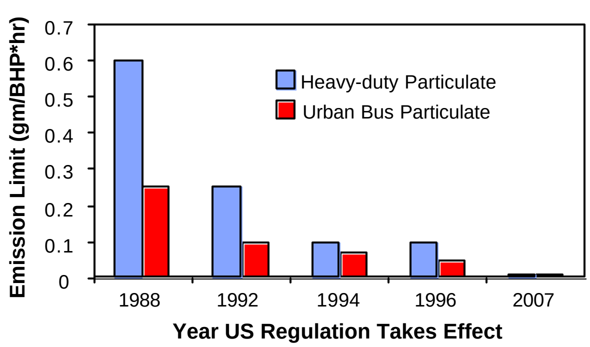

Figure 1: US Particulate Emissions Standards.

However, as soot is collected in the filter, the flow through the filter becomes restricted. The increase in flow restriction reduces the operating efficiency of the engine. High soot concentration in the filter can also lead to

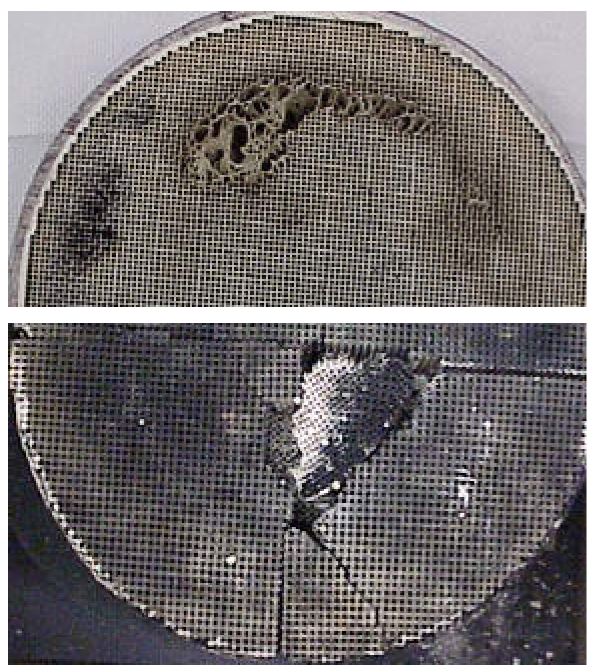

Figure 2: Sections of melted and cracked cordierite soot filters damaged during uncontrolled regeneration.

uncontrolled oxidation. When this occurs, high temperatures or temperature gradients may lead to melting or cracking of the filter material (Figure 2). Even when the failure only affects a small fraction of the filter volume, filtration efficiency can be reduced by an order of magnitude. Controlled removal of the collected soot from the filter (or regeneration) is a major challenge.

There are two general approaches to regeneration. Regeneration is referred to as passive if no energy is added to the system to remove the soot. Passive regeneration systems typically use catalysts to lower the temperature at which soot oxidizes to the temperature of the exhaust stream. Passive regeneration systems fail to remove soot when exhaust temperatures are low throughout the duty cycle, as in many light- and medium-duty applications.

Active regeneration is the removal of soot through adding energy. This is typically done through heating. Examples of active regeneration systems that add heat include fuel burners,[1] electrical heaters,[2] engine management, and microwave.[3,4,5] Catalysts may or may not be used in active systems. Active regeneration systems may operate at lower restriction than passive soot filters, but the cost of the added energy will likely result in a higher fuel penalty than passive systems.

Microwave Heating

The ability of a material to be heated with microwaves is dependent on the dielectric properties. The dielectric constant is composed of real, e', and imaginary , e'', components (Equation 1). These represent respectively a material's ability to store and

$$e = e' + j e''$$

dissipate electromagnetic energy. The dielectric constant of a material varies with temperature, frequency, and composition.

The power absorbed, p, is proportional to the imaginary portion of the dielectric constant, the frequency, f, and the electric field, E_{in} (Equation 2). Values for the

$$p = 2p\, f e_0 e'' \mathrm{E}_{in}^{2}$$

dielectric constant of diesel soot and cordierite are given in table 1.[6] The imaginary portion of the dielectric constant is much larger for soot than for cordierite.

When soot on a cordierite filter is exposed to microwaves, the soot is heated directly by the microwaves while the cordierite is heated only by conduction or convection from the soot. The ability to selectively deposit heat is a primary motivation for the use of microwave heating.

Microwaves penetrate some distance into dielectric materials. The penetration depth, D_p, is a function of the dielectric constant and frequency, with greater penetration when frequency and complex dielectric constant are low (Equation 3). The penetration of microwaves allows the delivery of energy to inner portions of a solid body, which results in more uniform heating

$$D_p = \frac{c}{2pf\sqrt{2e'}} \frac{1}{\sqrt{\left[1+\left(\frac{e''}{e'}\right)^2\right]^{0.5} - 1}}$$

Two other aspects of microwave heating recommend it over other active heating approaches. First, no electrical connections are required in the exhaust stream. Second, the exhaust stream is not heated directly.
The importance of not heating the exhaust stream is illustrated in Figure 3. Model heating curves for a Fleetguard/Nelson (FGN) fiber wall-flow filter with several

Sample	ε'	ε''
Soot	8.6	7.4
Cordierite	1.0008	0.00006

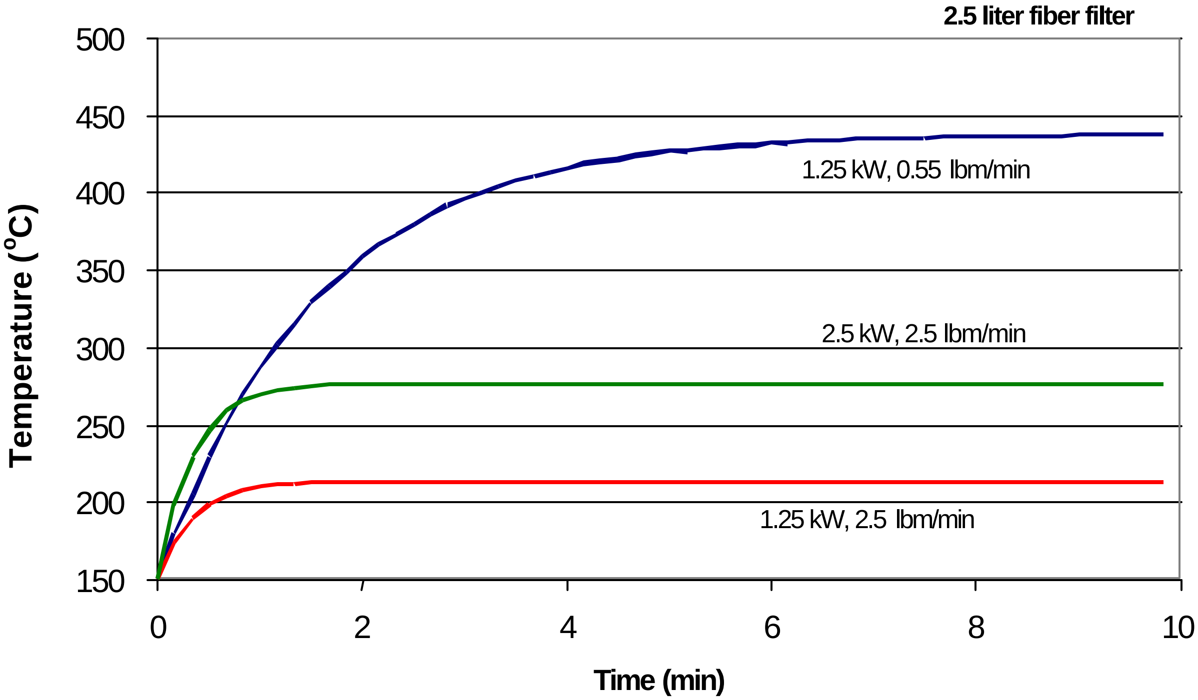

Figure 3: Modeled heating trajectories for a Fleetguard filter.

exhaust flow-rates and energy deposition rates are shown. An elementary model for uniform heating of a filter substrate in an exhaust stream was used. As a first order approximation, convection and conduction were neglected. It was assumed that the exhaust stream and the filter had identical temperatures at all times. This assumption causes efficiency overestimation for systems that heat the exhaust directly, and underestimation for systems that heat the filter media or soot directly.

The final temperature is greatly affected by the mass air flow rates. At higher flow rate, the quantity of heat removed by the exhaust is too great to allow high temperatures to be achieved. Even when the heat input is doubled the final temperature is not raised to a temperature where regeneration might occur. This model demonstrates the advantage of a system that does not directly heat the exhaust stream. and the benefit of reducing the exhaust flow during regeneration.

In summary, the advantages of microwave heating over other active heating regeneration systems are a) the direct and selective energy deposition, b) the penetration of microwaves to heat inner portions of a solid, c) the lack of moving parts or electrical connections in the exhaust stream, and d) the lack of direct exhaust stream heating. Microwave systems have a few disadvantages as well. The multiple energy conversions required from the fuel to microwave energy reduce the overall system efficiency. Additionally, the safety issues associated with preventing human microwave exposure will require careful engineering.

System Development

The system development has been separated into three interdependent tasks: microwave system development, filter development, and system and controls integration.

Microwave system development includes the design of the microwave cavity (which serves as the filter can), design of the waveguide system, and specification of the power supply and microwave generator. The microwave cavity is the only portion of the system that does not consist of strictly off-the-shelf components. Tools used in cavity design include modeling of the microwave fields, bench-scale testing of heating, and engine test-cell evaluation of performance. Dielectric measurements have been performed so that accurate properties for filter materials, catalysts and ash can be used in the modeling.

A schematic drawing of the current laboratory and test-cell microwave system is shown in Figure 4. A production system would include only the generator, microwave cavity, a short section of waveguide connecting them, and a power supply (not shown). The other components shown in the schematic are necessary only for a developmental system where the cavity and filter characteristics are not fixed.

***Filter development*:** In conjunction with the microwave system development, Fleetguard (FGN) has spent some effort developing an advanced wall-flow fiber filter. The filter media is composed primarily of alumina fibers. The media is rolled to form a corrugated spiral-wound filter preform. The preform is then impregnated with a refractory ceramic binder to increase strength and provide for high temperature capability.

The FGN filter has high porosity and surface area relative to the conventional extruded monolith wall-flow filters. Consequences of the high porosity include low restriction and a low thermal mass. The FGN filter also has a greater tolerance for thermal gradients than conventional wall-flow filters.

The importance of a low thermal mass can be demonstrated using the same elementary heating model used earlier. Figure 5 compares modeled heating curves for cordierite and FGN fiber filters. The FGN filter has a volumetric density less than 1/3 that of the cordierite filter, so for equal filter volumes the initial heating rate of the FGN filter is more than triple that of the cordierite filter. This higher initial heating

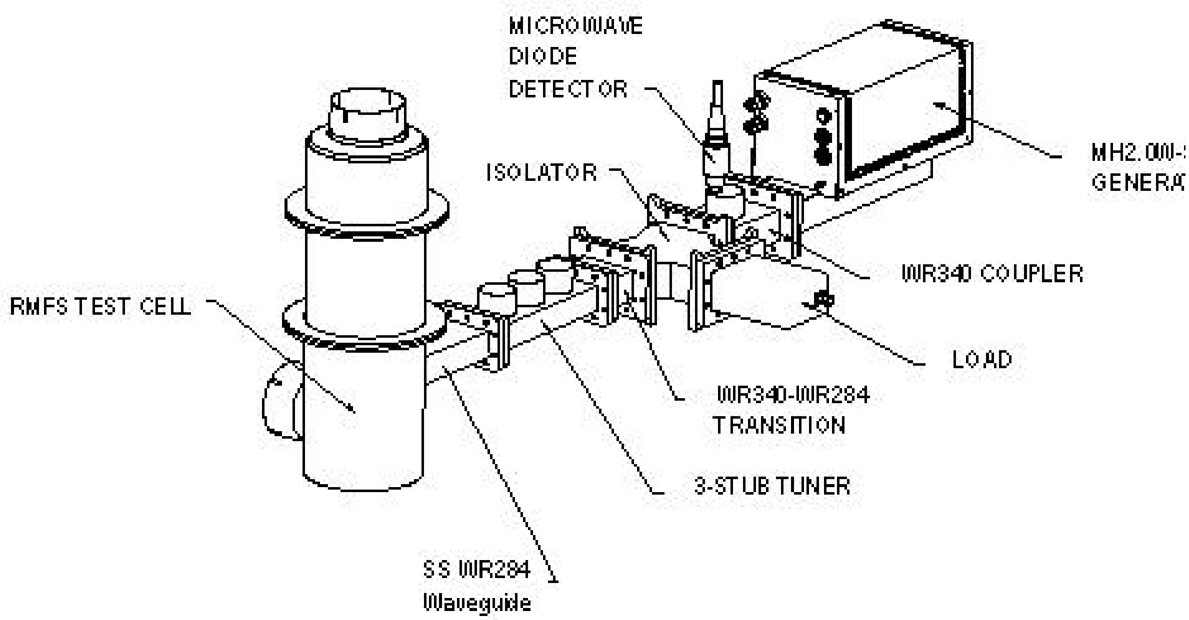

Figure 4: A schematic of the microwave system.

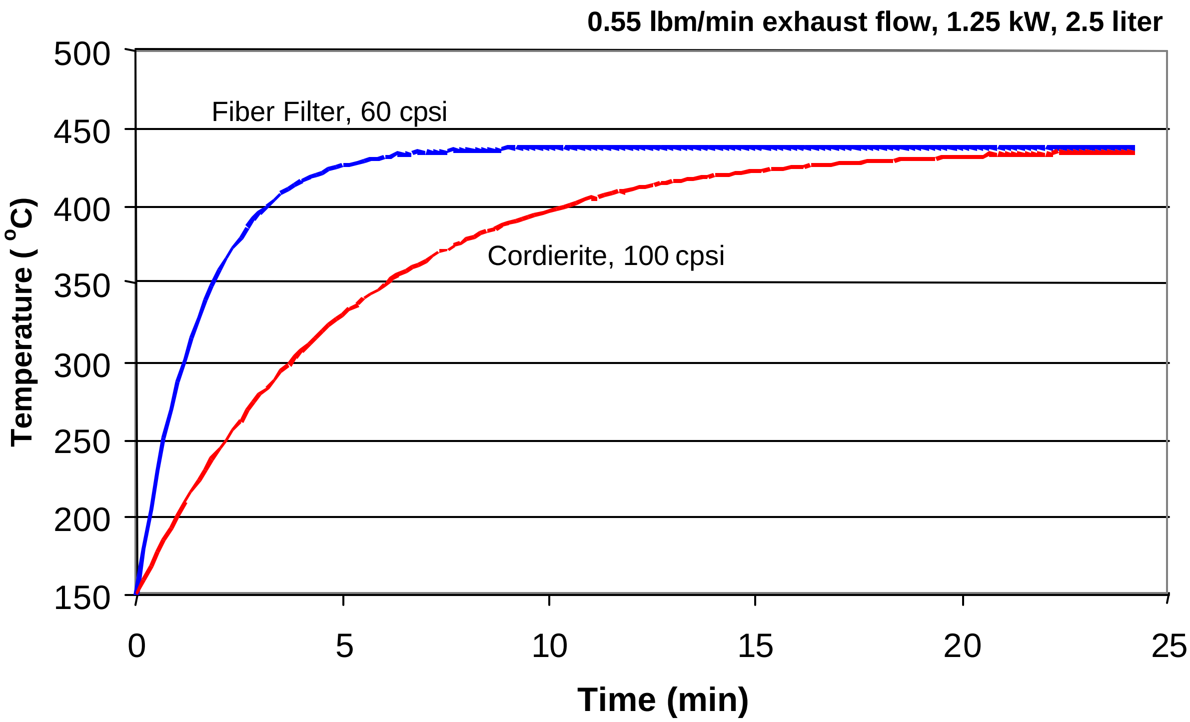

Figure 5: Effect of filter mass on required heating time.

rate significantly decreases the time required to reach regeneration temperatures.

Initially, the refractory binder used was silicon carbide (SiC) deposited via Chemical Vapor Infiltration (CVI). Coatings deposited in a laboratory-scale reactor were tough and uniform. However scaling up to a production-scale reactor resulted in low-strength filters with non-uniform coatings. When some of the most uniform specimens were heated in a microwave cavity, portions of the filters reached SiC oxidation temperatures, while other portions failed to reach soot oxidation temperatures. Figure 6 is a photograph of one of these filters, which overheated near the middle.

The non-uniformity in the production-scale CVI coatings is likely due to the complexity of the diffusion fields in a furnace loaded with a large number of filter preforms. Other refractory ceramic coatings and processes are currently being investigated.

System and controls integration. Figure 7 shows a microwave assisted particulate regeneration system installed in a test cell on a bypass stack of a 5.9L Cummins ISB engine. A time-temperature profile collected during microwave heating of a CVI SiC filter is shown in Figure 8. The thermocouple was positioned in the exhaust stream just after the microwave cavity.

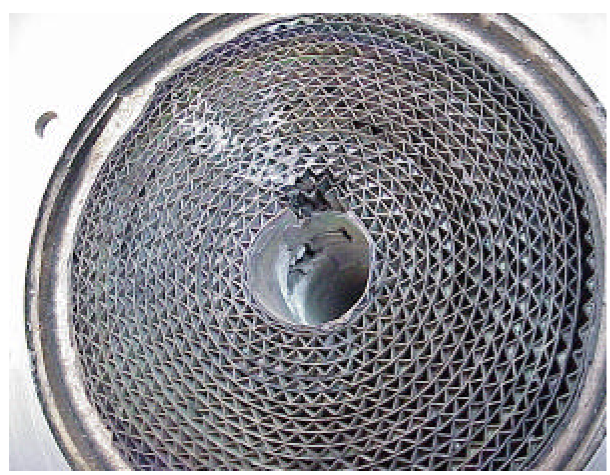

Figure 6: Overheated SiC fibrous filter

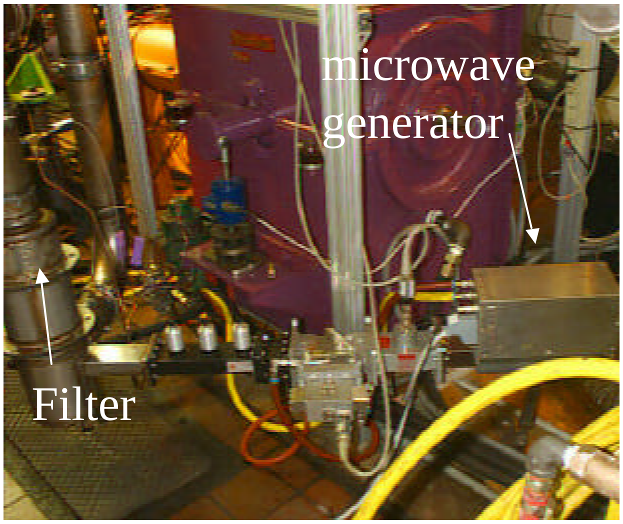

Figure 7: Microwave system connected to a 5.9-liter Cummins ISB in a test cell.

Shortly after microwave power was applied, the temperature of the exhaust stream began to rise. After about ten minutes of heating with 1kW of power there was a sudden increase in the rate of heating. This is similar to the sudden temperature rise seen in uncontrolled regeneration, when a large amount of soot is oxidized in a short period. The peak temperature achieved here is much lower than peak temperatures observed in uncontrolled regeneration, probably because the soot loading was low (3 g/liter).

Figure 9 displays a series of reference condition backpressure measurements during the initial loading and several subsequent regeneration-loading cycles of a CVI-SiC filter. The filter was loaded to 10g/liter of soot before each regeneration episode. For all of the regeneration episodes shown, the microwave generator was operated at 2.0 kW of power and the exhaust mass flow rate was near 0.55 lbm/min.

The first regeneration episode consisted of five hours of continuous heating. After that regeneration episode, the pressure drop across the filter (backpressure) had decreased by 10″ H_2O to 8.5″ H_2O.

The last two regeneration episodes shown were performed in 10 minute segments. After each 10 minute heating interval, the

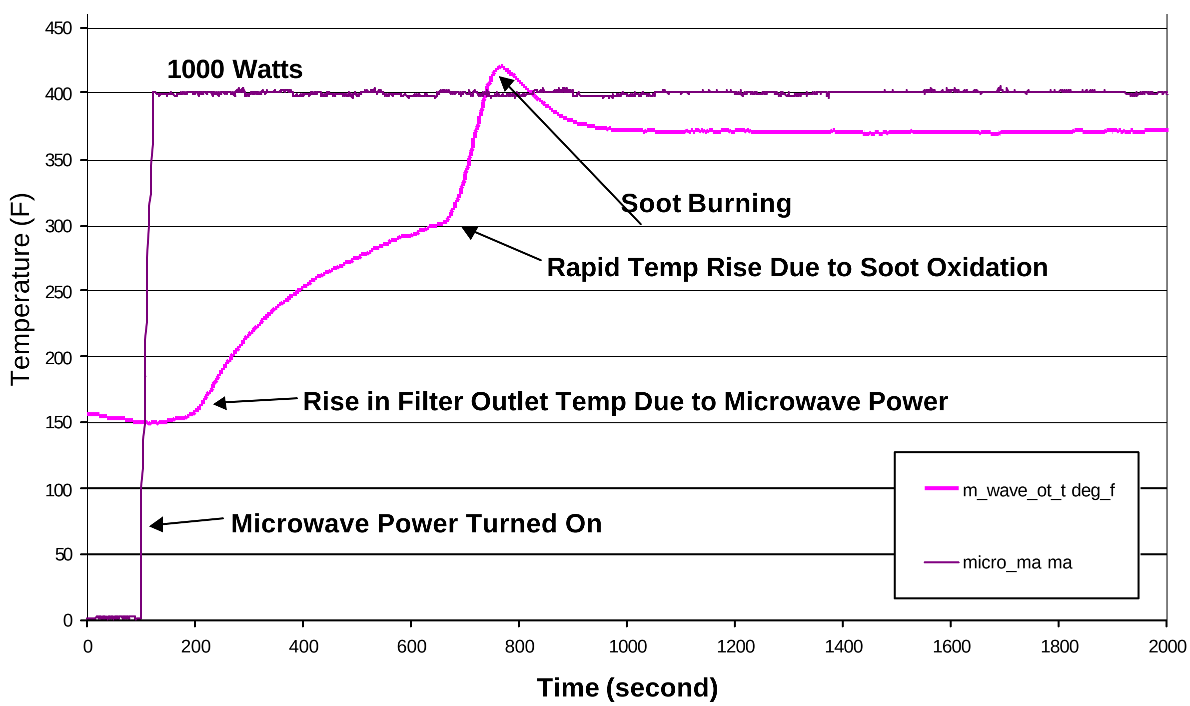

Figure 8: Filter outlet exhaust temperature profile during microwave heating

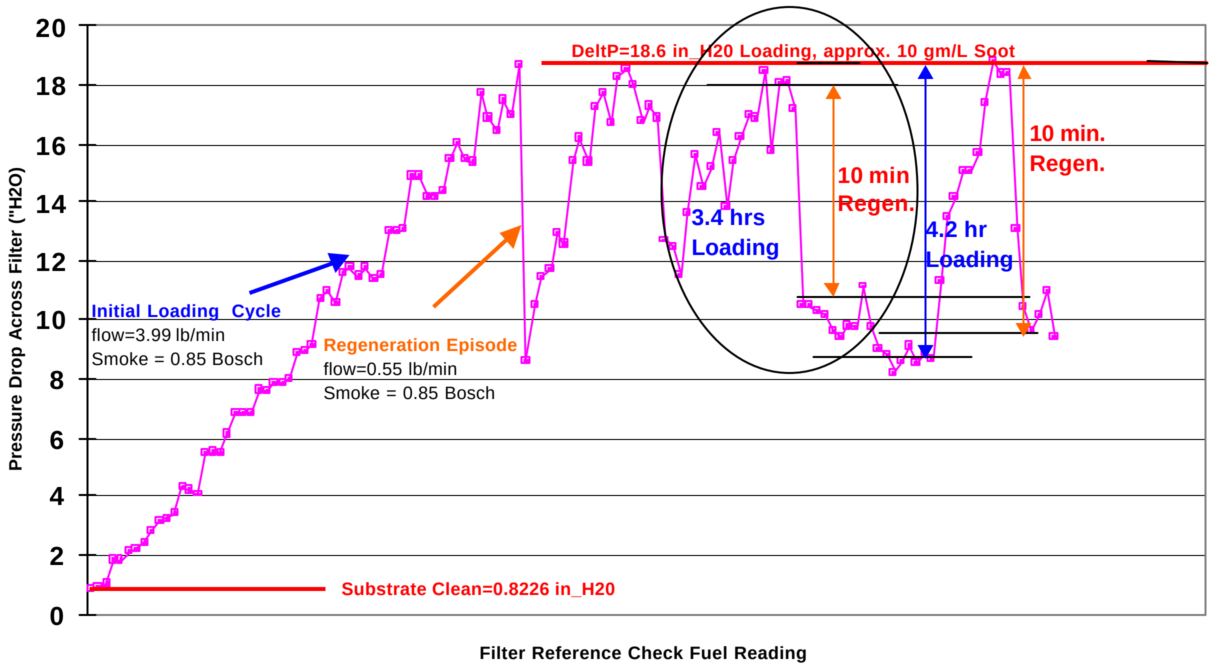

Figure 9: Several soot loading and regeneration episodes

flow rate was increased to the reference condition (3.99 lbm/min), the filter and engine were allowed to stabilize, and then the backpressure was recorded. After recording the backpressure, the flow was again lowered to the 0.55 lbm/min heating condition and microwaves turned on.

During the last two regeneration events the largest backpressure decrease occurred during the first 10 minute heating cycle. Based on this observation, regeneration appears to require less than 10 minutes of heating. The difference between the post-regeneration backpressure and the clean filter backpressure is due to unburned soot left in the filter. Improved cavity design and filter materials should decrease both the amount of soot left unburned and the post-regeneration backpressure.

The microwave assisted particulate filter regeneration system has operated reliably for more than 100 hours in the test cell. Exhaust temperatures measured after the filter have been as much as 260°C above the inlet exhaust temperature. Seven regeneration events have been induced using microwave heating.

Current tasks

Because of the non-uniformity of the CVI SiC filters, new filters made using alternative processing methods have been produced. These filters are currently being evaluated in the microwave system. The effects of soot loading, exhaust flow rate and inlet temperature, and microwave power and heating duration are being determined. Additionally, the use of a supplemental air source is being evaluated.

Alterations to the cavity geometry to improve the regeneration performance are being made.

Conclusion

Key advantages of microwave heating over other active regeneration systems include a) direct and selective energy deposition, b) penetration of microwaves to heat inner portions of a solid, c) a lack of moving parts or electrical connections in the exhaust stream, and d) a lack of direct exhaust stream heating.

A laboratory microwave assisted particulate regeneration system has been developed. Microwave assisted regeneration has been induced during after heating for 10 minutes or less. The system has operated reliably for more that 100 hours in a test cell. Although total regeneration was not observed, there are still opportunities for improving performance through a better understanding of the effects of operating conditions, improved microwave cavity design, and improved filter materials.

Acknowledgements

The support of the Department of Energy is under the PNGV program and the Advanced Materials for High BMEP Engines program is gratefully acknowledged. In addition, this work would not have been possible without the help of Alan Hammond, Tom Yonushonis, Brian Blackwell, Cheryl Sellers, Rahul Mital, and Bradlee Stroia at Cummins; Bill Haberkamp, Ray Cheng, and Mark Allie at Fleetguard/Nelson; and David McDonald and Jerry Wessel at Richardson Electronics.

---

[1] McDonald, J.S., Simon, G.M., "Development of a Particulate Trap System for a Heavy-Duty Diesel Engine", SAE 880006.

[2] Kojetin, P., Janezich, F., Sura, L., Tuma, D., "Production Experience of a ceramic Wall Flow Electric Regeneration Diesel Particulate Trap", SAE 930129.

[3] McDonald, A.C., Yonushonis, T.M., Haberkamp, W.C., Mako, F., Len, L.K., Silberglitt, R., Ahmed, I., "Microwave Regenerated Particulate Trap", Proceedings of the 3rd Annual Diesel Engine Emissions Reduction Workshop, (1997), pp 247-252.

[4] McDonald, A.C., Yonushonis, T.M., Haberkamp, W.C., Danko, G., Silberglitt, R., "Regeneration of a Diesel Engine Particulate Filter Using Microwave Heating", Proceedings of the 5th Annual Diesel Engine Emissions Reduction Workshop, (1999), pp V-97…V-99.

[5] Walton, F.B., Hayward, P.J., Wren, D.J., "Controlled Energy Deposition in Diesel Particulate Filters During Regeneration by Means of Microwave Irradiation", SAE 900327.

[6] Suresh., B.V., Popuri, S., Gautam, M., Seehra, M.S., "Thermal and Microwave Characteristics of Diesel Particulate Matter in Relation to Microwave Regeneration of Traps", J. Applied Occ. and Environ. Hygiene, Vol. 11, No. 7 (1996), pp 799-803.