In-situ Crack Detection for Automotive Diesel Particulate Filters – extended summary

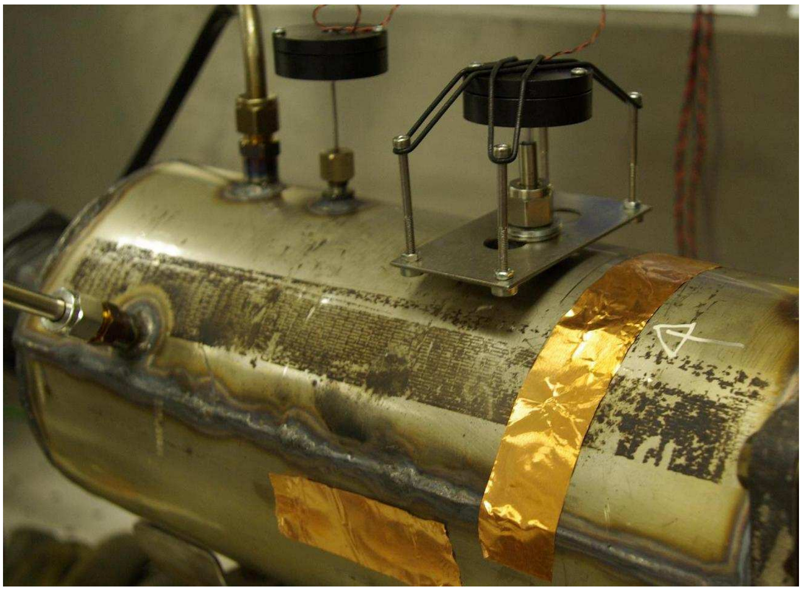
This work describes an *in situ* technique capable of measuring filter vibration events which may be associated with thermal crack damage. A surface microphone coupled directly to the filter substrate through a hole in the can and intumescent matting measures brick vibration, while a background detector measures exhaust pipe and canning vibration events in order to discriminate metallic thermal expansion. Vibration and internal thermocouple data is presented from exothermic regenerations for several different filters loaded with soot on a commercial Diesel Particulate Generator with standard Diesel fuel and fuel treated with a catalytic additive. The extension of the technique to testing on a vehicle is demonstrated.

Diesel Particulate Filter (DPF) soot load capacity is sometimes limited by a thermal crack failure mechanism associated with high temperature gradients which can occur during regeneration – particularly at low exhaust flow rates. The filter material and construction can be optimised for resistance to thermal cracking, however, the precise conditions which give rise to thermal failure of parts can be difficult to establish accurately and repeatably. For instance, thermal failure of parts may occur at the onset of the heating due to the exotherm of trapped soot, or during cooling (when the exhaust temperature can fall rapidly). The time of occurrence of thermal failure can help to establish the worst conditions for filters.

During regeneration testing of DPFs on a burner- based Diesel Particulate Generator (DPG) it was noted that damage was often associated with an audible crack noise. The use of acoustic emission for detecting cracks in concrete and asphalt is well established.

Initial tests used a microphone to record these events, but the ambient noise level makes this difficult. A custom surface microphone has been developed which can be coupled directly to the DPF surface. A second microphone coupled to the DPF canning can be used to reject 'ticking' due to thermal expansion of the metal can and exhaust system.

The photo below shows the brick sensor and O rings used to couple it to the brick (RHS). In a vehicle installation, these allow the sensor to be mounted upside down.



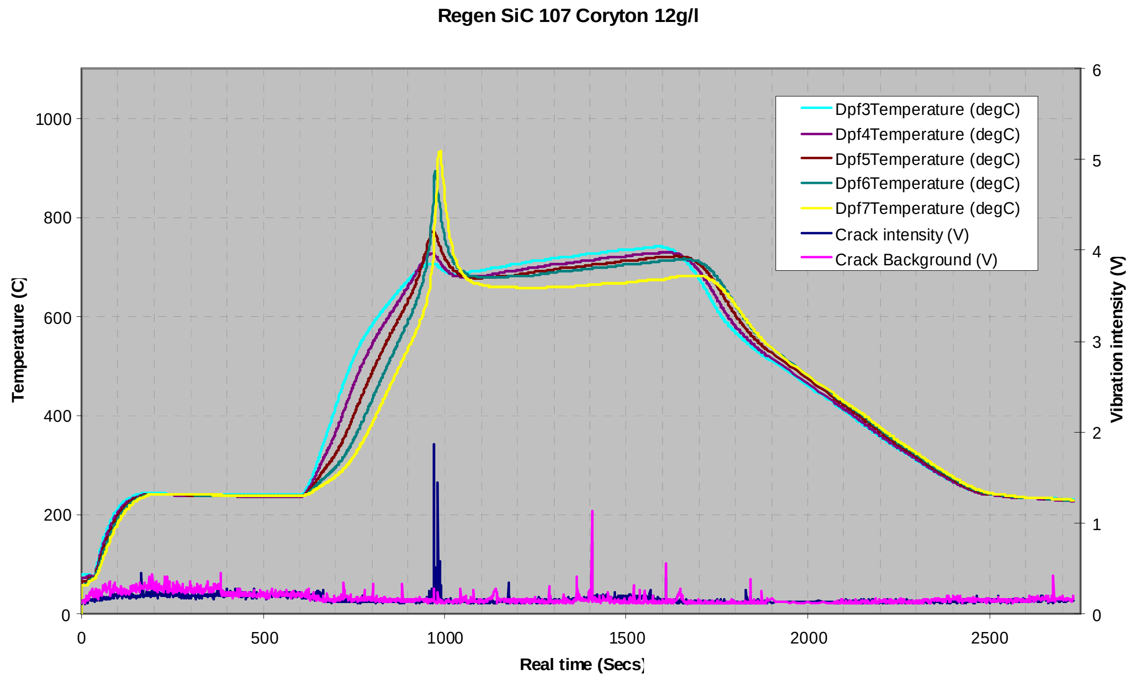
A background sensor (left hand side) is coupled directly to the can via a 1.6mm compression fitting. The signals from this can be used to reject vibration events due to thermal expansion of the can/ exhaust pipe.

Raw signals from these sensors were filtered to emphasise the crack activity (using a digital high pass filter). This gives good discrimination of 'cracks' from background vibration – both on the DPG and also on a DPF fitted to a vehicle running on a chassis dynamometer.

This study explored the utility of these microphones in Maximum Soot Load (MSL) testing using the DPG to closely simulate a vehicle 'Cut to Idle' test – where a DPF which is loaded to a prescribed level (in grams soot/l) is heated to the onset of regeneration and the exhaust flow rate reduced to ~60kg/hr with an overall lean AFR – giving inlet temperatures rising to ~700°C.

The resulting exotherm is monitored by thermocouples located within the DPF, together with the signals from the Brick and Background crack detectors. Two types of uncoated DPF were investigated, both ~ cylindrical with ~3l volume – an Aluminium Titanate monolith and a Silicon Carbide segmented part. Normal fuel and fuel doped with a catalytic additive to aid regeneration were tested.

The graph below shows the simulated Cut To Idle test with axial thermocouples, together with the crack signals for the SiC part loaded to 12g/l soot without the fuel additive. Brick vibration activity associated with the exotherm (blue trace) is clearly resolved



In conclusion, the poster demonstrates *In situ* vibration detection of DPFs. In particular:

1. Useful signal to noise ratio is demonstrated on a Diesel Particulate Generator and an engine
2. A background sensor can be used to compensate for the effects of vibrations associated with nearby metal expansion (can/ exhaust pipe)
3. Significant vibration events are sometimes associated with visible DPF cracks. They are generally associated with maximum temperature gradients
4. The addition of a catalytic fuel additive significantly reduces the sootload before damage for these tests (note that the regeneration strategy which is different for fuel with additive will affect this conclusion).
5. For the parts tested, the SiC DPF crack events produced larger signals than the AT DPF.

In-situ Crack Detection for Automotive Diesel Particulate Filters

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Summary

This work describes an *in situ* technique capable of measuring filter vibration events which may be associated with thermal crack damage. A surface microphone coupled directly to the filter substrate through a hole in the can and intumescent matting measures brick vibration, while a background detector measures exhaust pipe and canning vibration events in order to discriminate metallic thermal expansion. Vibration and internal thermocouple data is presented from exothermic regenerations for several different filters loaded with soot on a commercial Diesel Particulate Generator with standard Diesel fuel and fuel treated with a catalytic additive. The extension of the technique to testing on a vehicle is demonstrated.

Introduction

Diesel Particulate Filter (DPF) soot load capacity is sometimes limited by a thermal crack failure mechanism associated with high temperature gradients which can occur during regeneration – particularly at low exhaust flow rates. The filter material and construction can be optimised for resistance to thermal cracking, however, the precise conditions which give rise to thermal failure of parts can be difficult to establish accurately and repeatably. For instance, thermal failure of parts may occur at the onset of the heating due to the exotherm of trapped soot, or during cooling (when the exhaust temperature can fall rapidly). The time of occurrence of thermal failure can help to establish the worst conditions for filters.

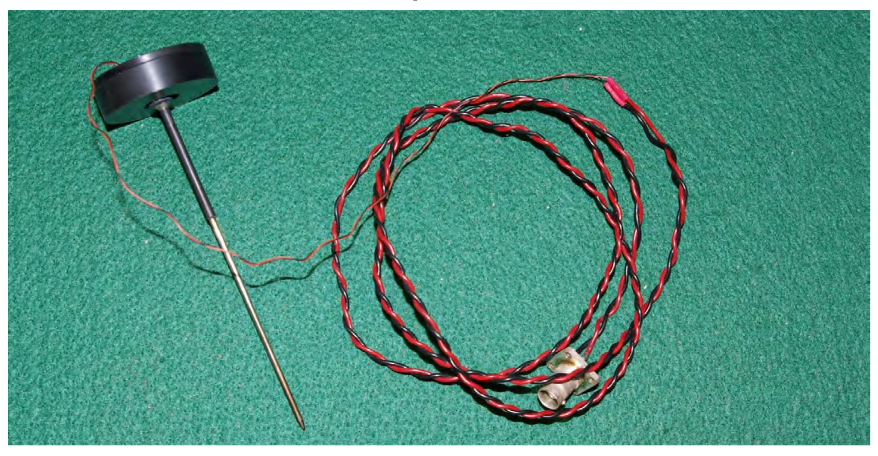
During regeneration testing of DPFs on a burner- based Diesel Particulate Generator (DPG) it was noted that damage was often associated with an audible crack noise. The use of acoustic emission for detecting cracks in concrete and asphalt is well established[1].

Initial tests used a microphone to record these events, but the ambient noise level makes this difficult. A custom surface microphone has been developed which can be coupled directly to the DPF surface. A second microphone coupled to the DPF canning can be used to reject 'ticking' due to thermal expansion of the metal can and exhaust system.

This study explored the utility of these microphones in Maximum Soot Load (MSL) testing – both on the DPG and also on a vehicle.

Equipment

In situ Surface Microphones



The photo above shows a picture of the surface microphone. The tip of the microphone is coupled directly onto the surface of the DPF (in the vicinity of expected cracks) by cutting a hole in the can and intumescent matting

The photo below shows the brick sensor and O rings used to couple it to the brick (RHS). In a vehicle installation, these allow the sensor to be mounted upside down.

A background sensor (left hand side) is coupled directly to the can via a 1/16" compression fitting. The signals from this can be used to reject vibration events due to thermal expansion of the can/ exhaust pipe.

Soot Loading and regeneration

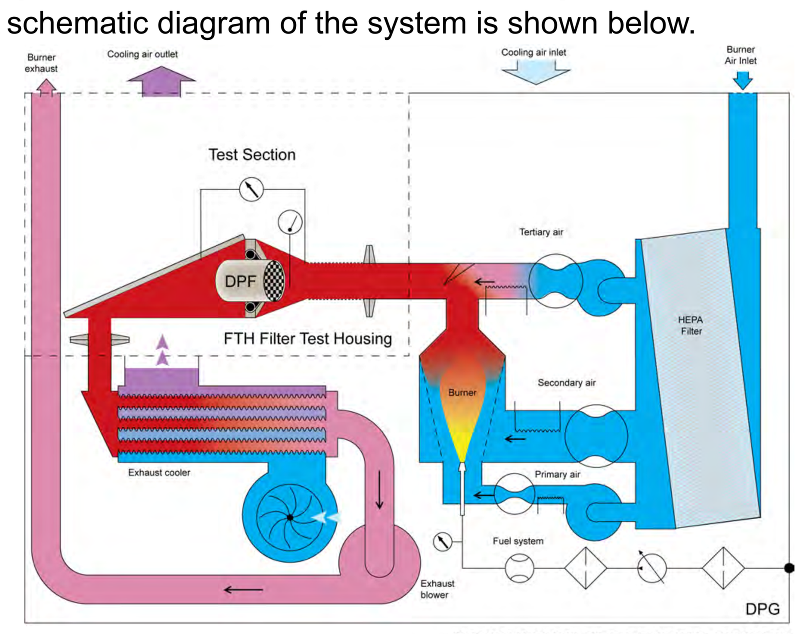
Parts were loaded and regenerated on a Diesel Particulate Generator (DPG) to soot concentrations from 8-15g/l.

For some tests, the fuel was doped with Eolys 176 transition metal additive at a rate of 500:1 (arranged to replicate the in-service concentration of catalyst in the soot).

Diesel Particulate Generator

The Cambustion DPG[2,3] incorporates a Diesel fuelled burner to generate similar soot particles to an engine.

A schematic diagram of the system is shown below.



CAMBUSTION DPF TESTING SYSTEM

The DPG setpoints were arranged to achieve the following:

- Loading of parts to prescribed sootloads
- Regeneration of loaded parts with a simulated 'Cut to Idle' (CTI) schedule where the loaded DPF is:
  - Heated to 240ºC at 250kg/hr
  - Flow reduced to ~60kg/hr, λ~3 (inlet temperature rises to ~700ºC).
  - Maintained at the high inlet temperature until soot oxidation is complete
  - Cooled slowly back to ~240ºC.

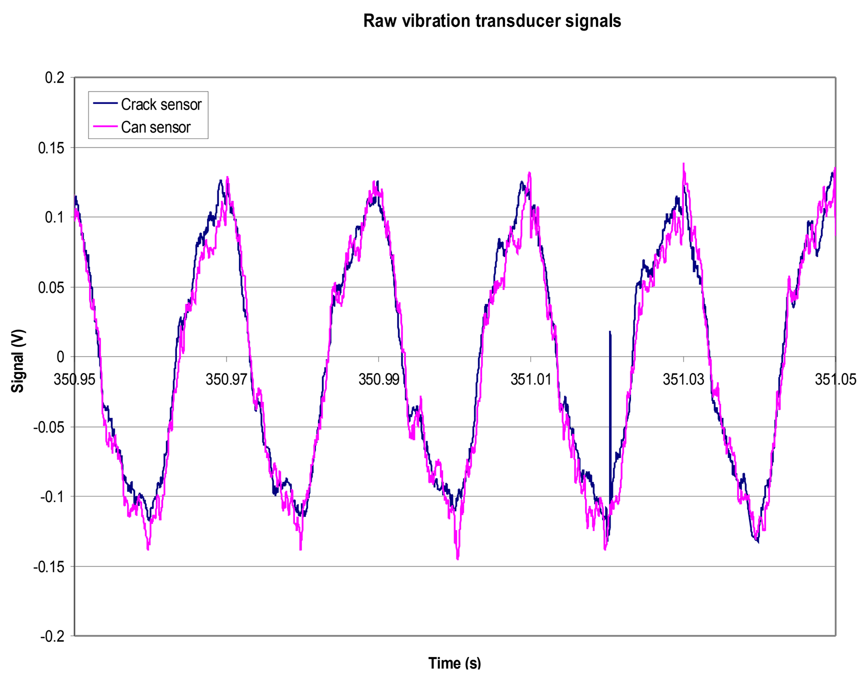
DPF test parts

Uncoated Silicon Carbide (SiC) and Aluminium Titanate (AT) DPFs of about 3l volume were used in the tests presented here. The parts were fitted with 25, 0.5mm thermocouples located to try and best resolve the DPF temperature field.

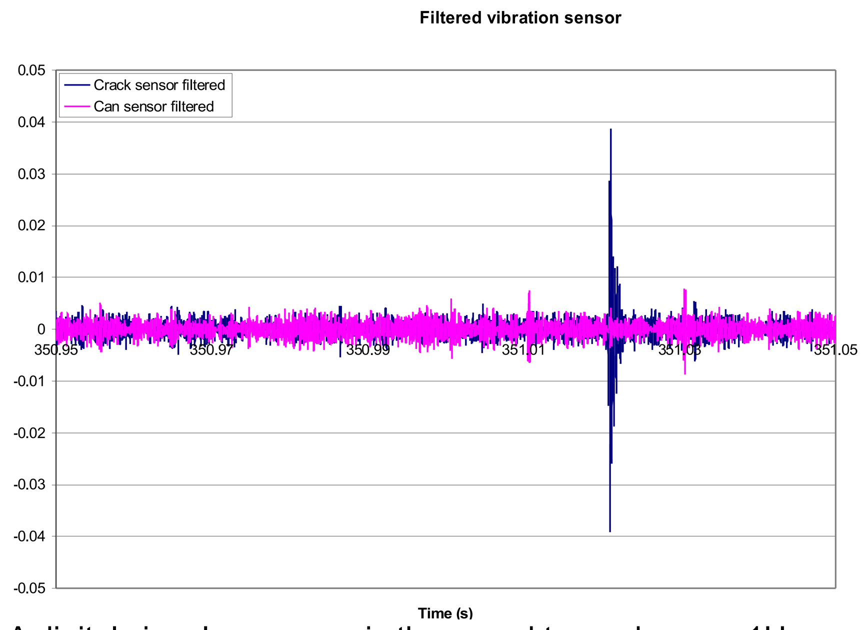
Results & Discussion

In Situ Vibration signals on DPG

Raw signals from the vibration transducers are shown below.



This shows an event at 351.02s superimposed with (50Hz) noise. Data is high-pass filtered at 3.5kHz to emphasize the vibration 'event'. The filtered signal is shown below

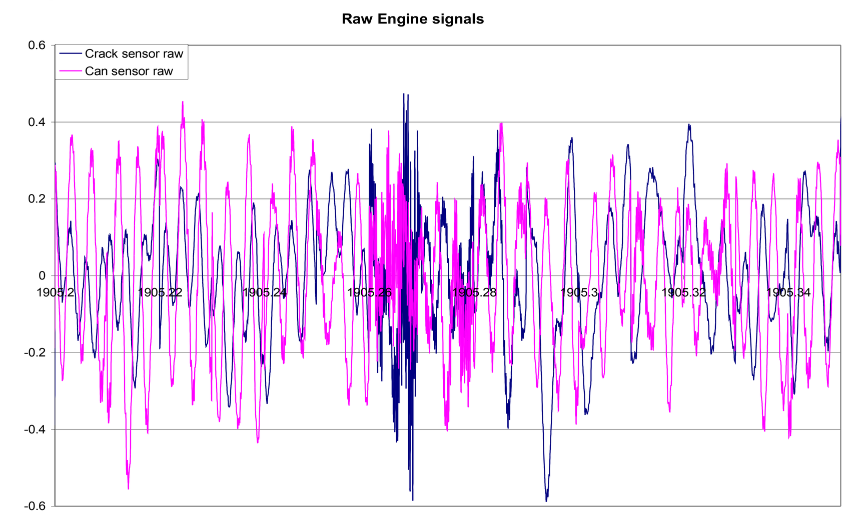


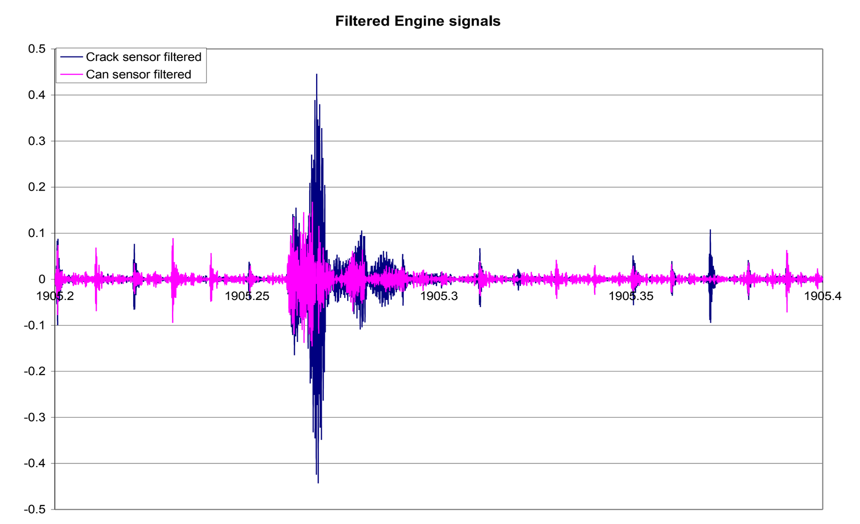
A digital signal processor is then used to produce a ~1Hz signal which corresponds to the peak to peak value of the filtered signals over a selectable window period. A ratio of the crack to the background signal can then be used to isolate brick events from background events.

In Situ Vibration signals on vehicle CTI

Typical data from a brick vibration 'event' from the sensors mounted on a DPF of a Peugeot 406 running a Cut To Idle test on a chassis dynamometer is shown below. The filter characteristics and signal processing were not changed for this test.

It is clear that the vehcle produces significantly more low frequency noise than the DPG, however, the crack event is still clearly visible. More sophisticated signal processing might be capable of improving the signal to noise ratio on the engine data.



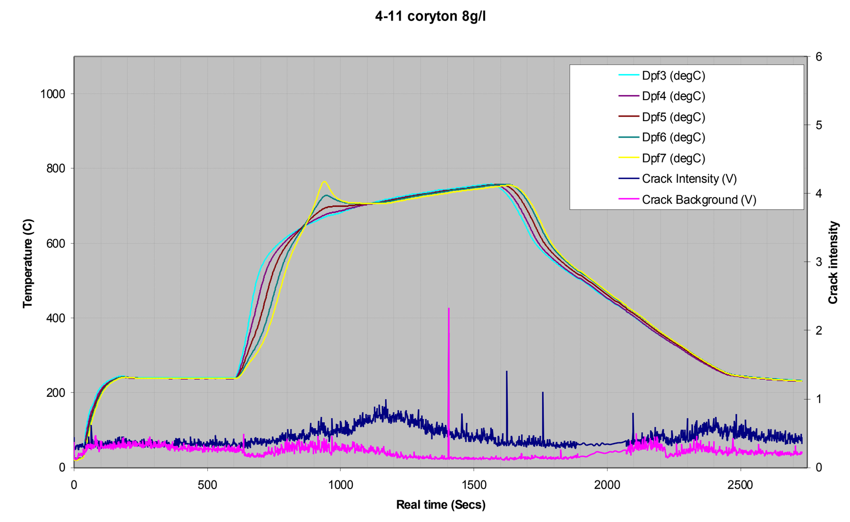


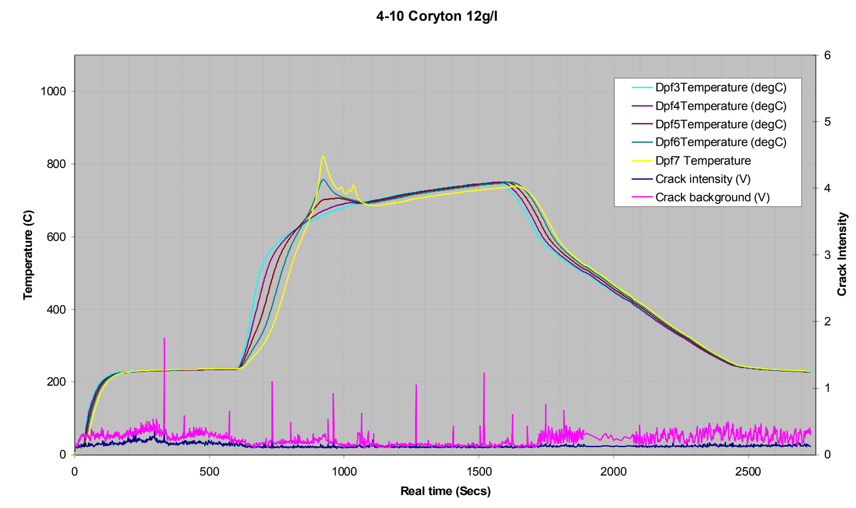
Sootload effect – AT DPFs

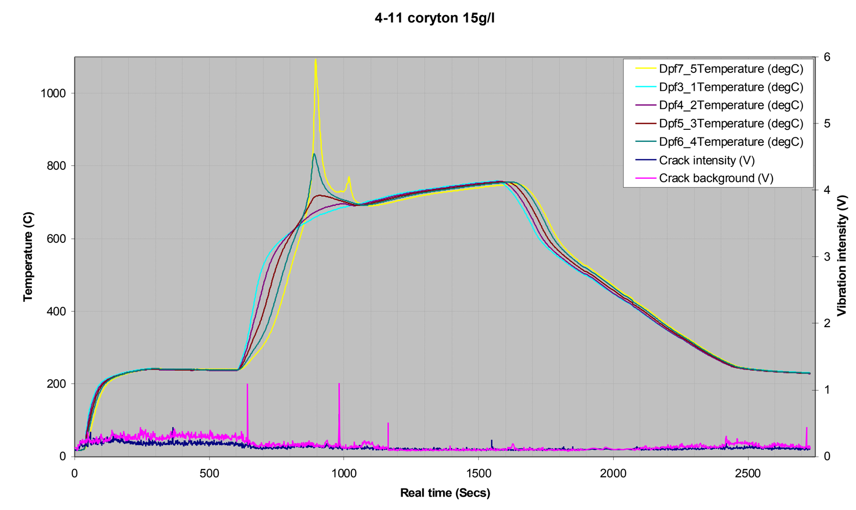
The following plots correspond to Cut To Idle regenerations conducted at 8, 12 and 15g/l sootload for an AT part.The thermocouples shown are located equally spaced along the DPF centreline.

The increasing exotherm as the sootload increases is evident. The crack transducers do not indicate significant 'events' on the brick apart from on the initial cooldown for the 8g/l regeneration. It is noted that the maximum temperature gradients can often occur during cooldown – when the engine/ burner is turned off (deceleration on a vehicle).

Near to the rear of the DPF, a repeatable 'double peaked' feature is noted for the higher soot concentrations. This feature is not observed for the SiC parts.



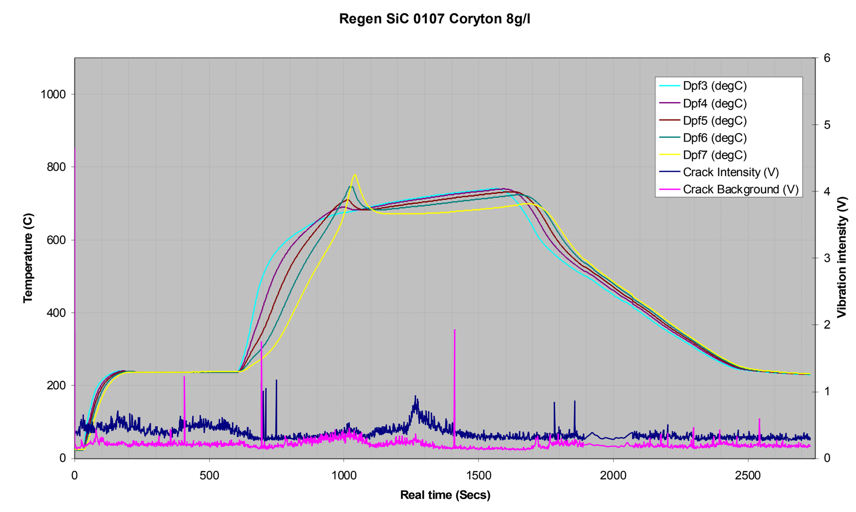


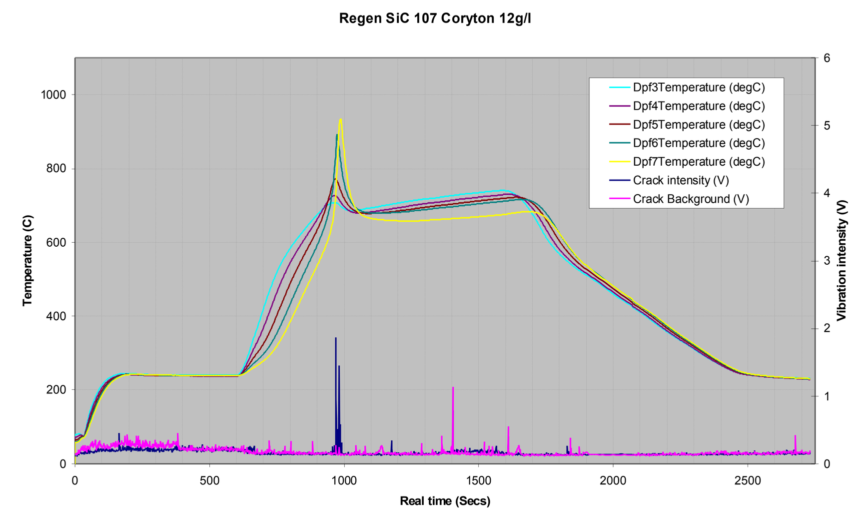


It is thought that intumescent mat 'popping' may be responsible for some of the 'background' effect on the brick crack intensity signal. No cracks were visible following these tests

SiC tests

The plots below correspond to Cut To Idle regenerations conducted on a SiC DPF at 8 and 12g/l

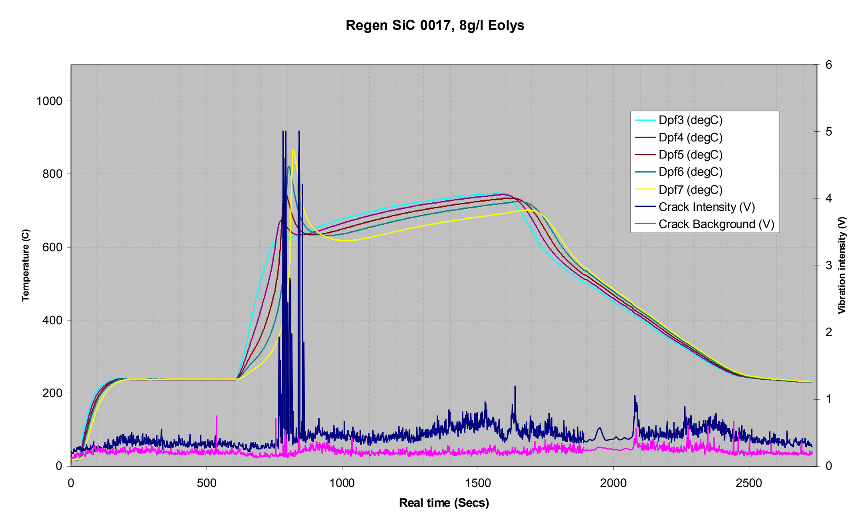


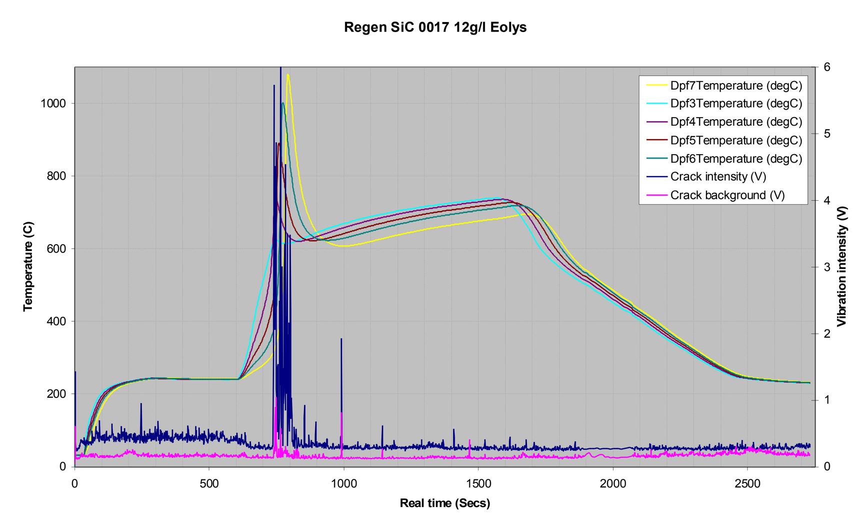


The 12g/l data shows significant brick vibrations associated with the exotherm. No cracks were visible following these tests

Fuel additive effects SiC

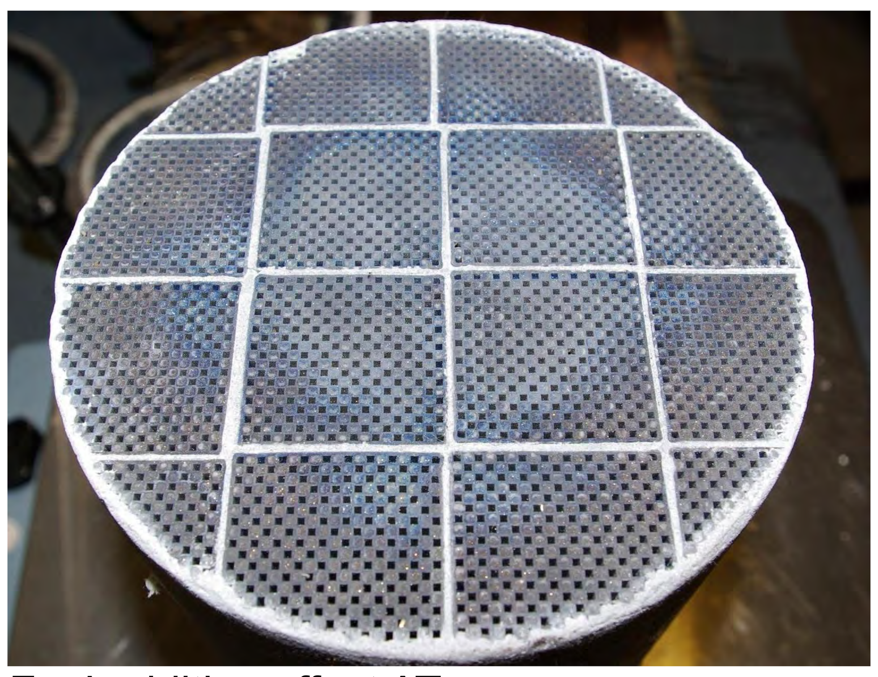
The plots below correspond to Cut To Idle regenerations conducted at 8 and 12g/l with Eolys 176 additive at 500:1.





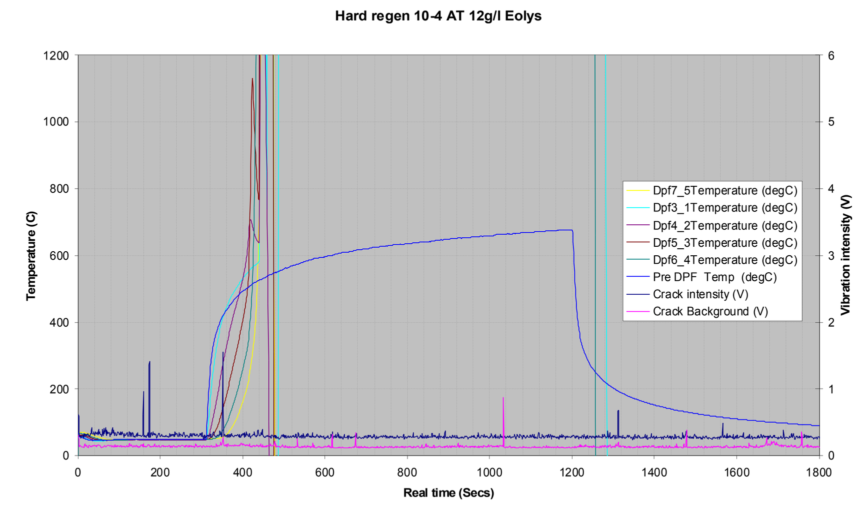
Both tests indicate significant brick crack events during the exotherm. Following the 12g/l test the filter was examined and 'ring' cracks were evident shown on the photo below.

The high temperatures at the rear face (~1100ºC) cause discolouration of the SiC material as seen below.



Fuel additive effect AT

The uncoated AT part was resistant to cracking. A very severe regeneration was conducted with a 12g/l sootload with Eolys 176 additive. In this test, the part was not preheated and the maximum temperatures caused failure of all internal TCs (T>1300ºC).



Following this test the part was cracked with a ring crack (see below). The crack data indicates that this might have happened at ~350s – although the signals are much smaller than for the SiC part.

Conclusions

In situ vibration detection of DPFs has been demonstrated.

1. Useful signal to noise ratio is demonstrated on a Diesel Particulate Generator and an engine
2. A background sensor can be used to compensate for the effects of vibrations associated with nearby metal expansion (can/ exhaust pipe)
3. Significant vibration events are sometimes associated with visible DPF cracks. They are generally associated with maximum temperature gradients
4. The addition of a catalytic fuel additive significantly reduces the sootload before damage for these tests (note that the regeneration strategy which is different for fuel with additive will affect this conclusion).
5. For the parts tested, the SiC DPF crack events produced larger signals than the AT DPF.

References

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2. "Performance Evaluation of Diesel Particulate Filters during Loading from Clean" K Reavell & T Hands. 13th Conference on Combustion Generated Nanoparticles, ETH Zurich, 2009.
3. "A New Instrument for Diesel Particulate Filter Functional Tests in Development and Quality Control Applications". T Hands *et al.* SAE Paper 2010-01-0809

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