Backpressure Characteristics of a DPF loaded with a Soot Generator and a Diesel Engine under Different Operating Cycles

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Introduction

The relationship between backpressure and soot load in a Diesel Particulate Filter (DPF) is important both directly for engine performance and for the accurate estimation of the soot load to trigger regeneration of the filter.

Previous work[1] has shown differences in the backpressure caused by equal loads of soot deposited by different engine operating conditions. In this work, the backpressure created by soot deposited at three different operating conditions was investigated, along with that produced by soot from the Cambustion DPG (Diesel Particulate Generator) system for testing DPFs with soot produced by a Diesel burner.

Equipment

All tests were performed on the same DPF to avoid sample variation. This was an uncoated cylindrical Silicon Carbide part, 5.66” diameter × 10” length. In all these tests, the filter remained canned.

Engine Loading

Engine loading was performed on a Euro 4 compliant 2 litre common rail Diesel engine. The engine exhaust system was fitted with a production Diesel Oxidation Catalyst (DOC) upstream of the DPF. The engine is mounted on dynamic dynamometer. Cycle simulation software controlling the dynamometer allowed simulation of three different engine operating cycles:

- New European Drive Cycle. On this engine, this produces soot at around 3g/h.
- A 'rural simulation' drive cycle producing soot at 6 g/h.
- Steady state operation with modified engine operating points generating soot at 10 g/h.

These cycles were repeated (ie. without cooling down) until the desired soot mass was accumulated.

DPG

The Cambustion DPG[1,2,3] incorporates a Diesel fuelled burner to generate similar soot particles to an engine. The burner operates at close to atmospheric pressure, with the particulate-laden flow drawn through the filter under test by a downstream blower so that variation in DPF backpressure does not cause variation in the soot generation as it may in an engine. DPF flow and temperature are controlled independently of the burner conditions. In these tests, the DPG testing was not fitted with a DOC.

The DPG loads parts with soot at similar conditions to light and medium duty Diesel engines, up to a flow rate of 400 kg/h at temperatures around 250ºC. For this work, the filter was loaded at 250 kg/h and 240ºC, at a soot rate of approximately 10 g/h.

Procedure

The DPF was regenerated on the DPG before all tests to ensure it was empty of soot by operating with an inlet temperature of 650ºC for 30 minutes. It was then weighed in the range 200 - 240ºC to establish the empty mass. The weighing was conducted at this temperature to avoid errors due to the variable absorption of water on the filter.

The backpressure was measured on the DPG: results were corrected to standard conditions of 1013.25 mbar atmospheric pressure, 25ºC and 300 m^3/h to compensate for variations in ambient conditions.

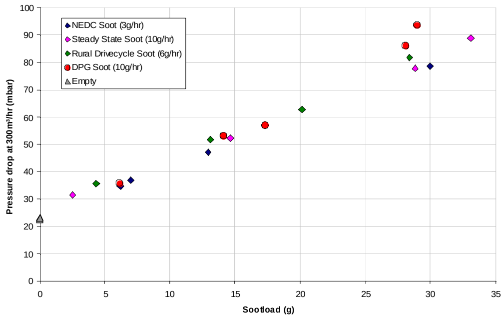
The filter was then loaded on the DPG or was transferred to the engine & dynamometer for loading. The loading was terminated at a time corresponding to the desired soot load and the estimated soot generation rate at that condition. The exact mass of soot was then established by repeating the high temperature weighing procedure and subtracting the empty mass.

The DPF was then refitted to the DPG for the loaded flow test. Before this flow test, the part was operated with a flow of 500 kg/h for 2 minutes to stabilise the deposited soot layer.

Results & Discussion

Backpressure at 300 m^3/h for soot from the different cycles and the DPG are shown in figure 1.

These results show very little difference between either the different operating conditions for the engine or for the engine and DPG. On the other hand, previously published[1] and also unpublished work has shown significant differences, particularly between soot deposited on a transient cycle and that produced at steady state on a dynamometer, where typically the steady state operation results in a higher backpressure for a given soot mass than the transient operation.



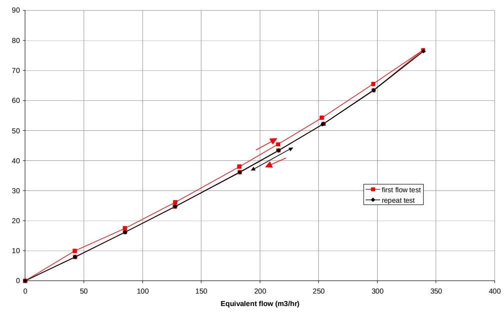


Figure 1: Backpressure vs Soot Load

Figure 2: Backpressure in Repeated Flow Sweeps

In order to investigate possible reasons for these results further investigations were performed.

Effect of High Flow on Soot Layer.

In the preliminary tests for this work, poor repeatability had been noted for flow tests made on loaded parts. The stabilisation phase was included in the loaded part tests above to eliminate this problem. When a loaded flow test was performed without this stabilisation phase, and then immediately repeated, the results shown in figure 2 were seen.

The backpressure measured in the first flow test (red) is higher as the flow scans up from zero than during the following downscan. Successive flow tests, black, then repeat up and down the characteristic of the downscan. This suggests that some permanent relaxation of the soot layer may occur at high flows.

Effect of Multistage Loading

The above tests were all performed with a single stage load from empty. When the engine loading was performed in two stages, with a cold start on the second phase, the final backpressure was lower than after the first stage of loading (figure 3). This effect was not observed in loading on the DPG, so to investigate whether this was an effect of the engine soot or cold start, a filter was loaded in two stages on the DPG, but with engine cold starts (with not enough running to produce significant soot load) part way through and at the end of loading. Flow tests before and after these engine cold starts showed a reduction in backpressure after the cold start (figure 4).

Conclusions

Diesel Particulate Filters loaded non-stop, without cold starts, by a variety of different cycles on a single engine, resulted in very similar soot mass : backpressure characteristics in this work.

The backpressure produced by soot generated by the DPG system is very similar to the engine soot.

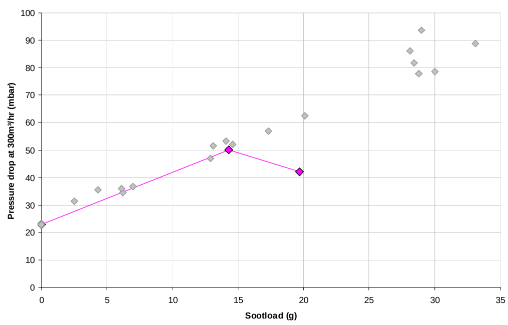
High flow conditions and cold starts produced significant reduction of the backpressure.

References

1.“A Standard Soot Generator for Diesel Particulate Filter Testing”. T Hands et al. Diesel Engine Emissions Reduction Conf. Aug 13-16 2007, Detroit

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



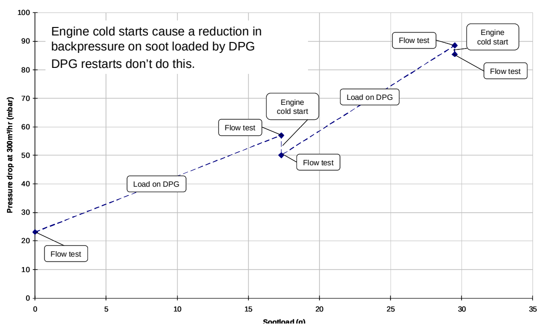


Figure 4: Backpressure Effect of Engine Cold Start

Figure 3: DPG Loading with Engine Cold Starts

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Summary

In this work, an uncoated SiC 5.66"dia ×10" DPF was loaded on a 2.0l Euro 4 Diesel engine mounted on a transient dynamometer under three different conditions, and by a Cambustion DPG (Diesel Particulate Generator) system. The loaded filters were weighed to determine the exact soot load and were flow tested with the DPG system to determine the backpressure vs. flow characteristic.

The different engine conditions were found to produce very similar backpressure at a given soot load. The soot generator was also found to produce a similar backpressure characteristic.

Further tests were conducted to investigate the effects of engine cold starts and high flow conditions on the backpressure characteristic of the deposited soot. The engine cold start was found to cause a permanent reduction in the backpressure of the soot cake on a DPF. For a DPF was loaded with soot, forcing a high flow rate (500 kg/h) of air through the filter was found also to cause a permanent reduction in the measured backpressure.

Introduction

The relationship between backpressure and soot load in a Diesel Particulate Filter (DPF) is important both directly for engine performance and for the accurate estimation of the soot load to trigger regeneration of the filter.

Previous work[1] has shown differences in the backpressure caused by equal loads of soot deposited by different engine operating conditions. In this work, the backpressure created by soot deposited at three different operating conditions was investigated, along with that produced by soot from the Cambustion DPG (Diesel Particulate Generator) system for testing DPFs with soot produced by a Diesel burner.

Equipment

All tests were performed on the same DPF to avoid sample variation. This was an uncoated cylindrical Silicon Carbide part, 5.66" diameter × 10" length. In all these tests, the filter remained canned: the engine exhaust and DPG test section were fitted with the same flanges to allow simple interchange of the part.

Engine Loading

Engine loading was performed on a Euro 4 compliant 2 litre common rail Diesel engine. The engine is mounted on dynamic dynamometer. Cycle simulation software[2] controlling the dynamometer allowed simulation of three different engine operating cycles:

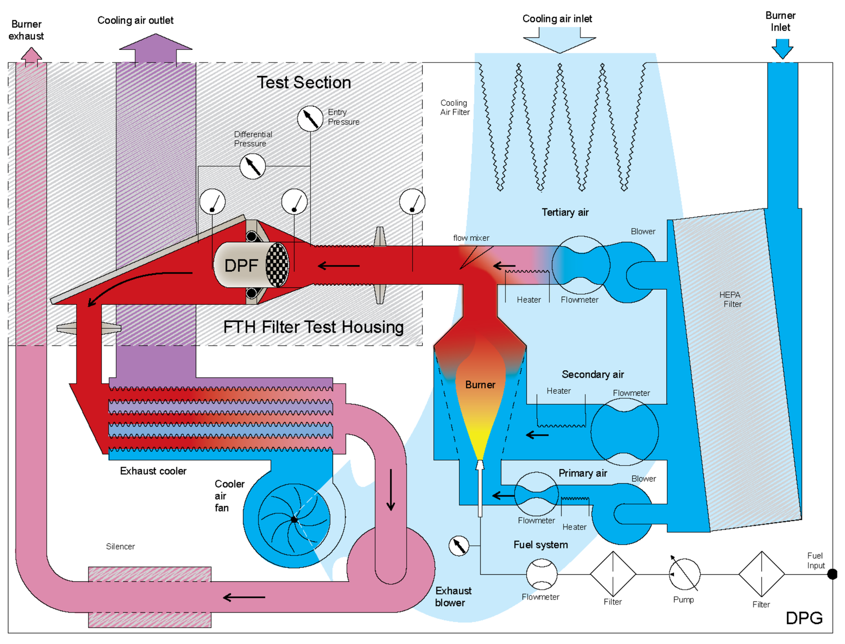
- New European Drive Cycle. On this engine, this produces soot at around 3g/h.
- A 'rural simulation' drive cycle producing soot at 6 g/h.
- Steady state operation with modified engine operating points to generate soot at a high rate of 10 g/h.

These cycles were repeated (ie. without cooling down between them) until the desired soot mass was accumulated.

The engine exhaust system was fitted with a production Diesel Oxidation Catalyst (DOC) upstream of the DPF: this is the most common application of uncatalysed DPFs such as this one.

DPG

The Cambustion DPG[3,4] incorporates a Diesel fuelled burner to generate similar soot particles to an engine. The schematic of the system is shown below.



CAMBUSTION DPF TESTING SYSTEM

The DPG burner operates at close to atmospheric pressure, with the particulate laden flow drawn through the filter under test by a downstream blower. This ensures that variation in DPF backpressure does not affect the soot generation as it can in an engine. The air and fuel flows into the burner are all measured. The output from the burner is mixed with an independently controlled 'tertiary' air flow: this allows accurate control of the DPF conditions without interfering with the soot generation.

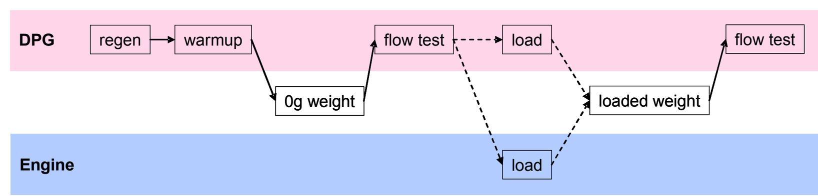
In this test programme, the DPG testing was not fitted with the DOC. This is to simulate best the application of the DPG for testing filters which are then used with an upstream DOC, currently the majority application. For single brick systems (used without DOC), the engine soot would differ mainly via higher levels of volatile components.

The DPG loads parts with soot at similar conditions to light and medium duty Diesel engines, up to a flow rate of 400 kg/h at temperatures around 250ºC. For this work, the filter was loaded at 250 kg/h at 240ºC, at a soot rate of approximately 10 g/h.

The DPG was also used in this work to regenerate the filter between tests and to perform the flow rate vs backpressure tests. The regeneration was achieved by raising the DPF inlet gas temperature to 650ºC for approximately 30 minutes. The flow tests were conducted at flows between 100 and 600 kg/h: the data reported here is the backpressure at 500 kg/h.

Procedure

All backpressure vs flow tests were made on the DPG in this work for best accuracy and comparability, with loading on the engine and DPG:



The DPF was regenerated on the DPG before all tests to ensure it was empty of soot. The filter was then fitted to the DPG to warm it up to between 200 and 250ºC for weighing to establish the weight of the (canned) filter without soot. The weighing was conducted at this temperature to avoid errors due to the absorption of water on the filter.

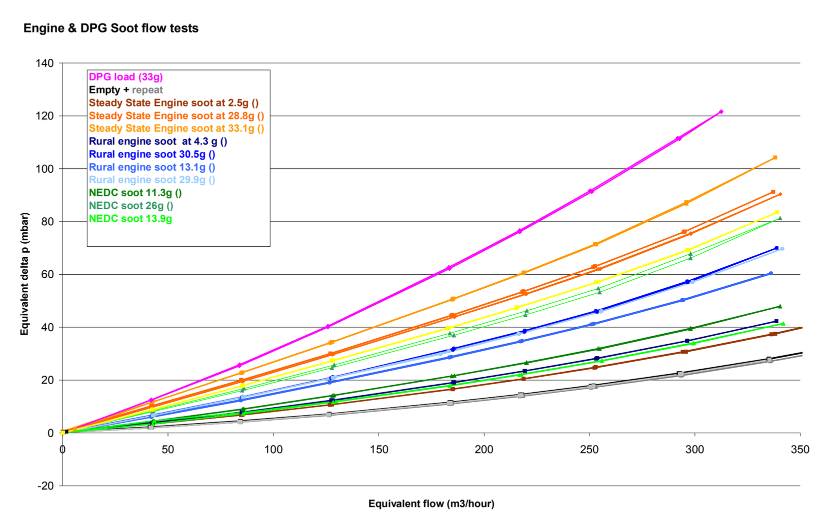
The backpressure of the filter was established by flow testing on the DPG. The flow in increased from zero to 500 kg/h and back in steps of 50 kg/h to characterise the backpressure of the filter. At each flow rate, the conditions are allowed to stabilise for 90s and then the pressure drop, temperature and inlet pressure are measured. The friction factor and Reynolds number, Re, (at nominal length scale) are calculated at each point, and then the backpressure at standard conditions of 300 m^3/h, 25ºC and 1 bar is calculated by interpolating this vector of results.

The filter was then loaded on the DPG or was transferred to the engine & dynamometer for loading. The loading was terminated at a time corresponding to the desired soot load and the estimated soot generation rate at that condition. The exact mass of soot was then established by repeating the high temperature weighing procedure and subtracting the empty weight.

The DPF was then refitted to the DPG for the loaded flow test. Before this flow test, the part was operated with a flow of 500 kg/h for 2 minutes to stabilise the deposited soot layer.

Results & Discussion

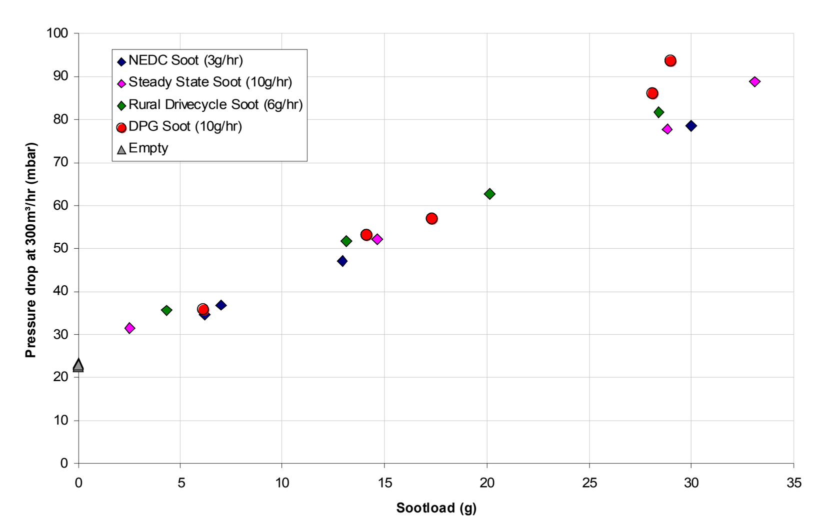
The results from the flow test curves are plotted below, as described above these are referred to a flow rate at the standard conditions corresponding to the Reynolds number of the test, assuming friction factor is a function of Re only:



The backpressure results for each test at 300 m^3/h interpolated from these curves:

Soot Type	Soot Load (g)	dP at 300m3/hour (mbar)
Empty	0.0	23.5
Empty	0.0	22.6
Empty	0.0	23.1
Empty	0.0	22.9
NEDC	6.2	34.7
NEDC	7.0	36.7
NEDC	12.9	47.0
NEDC	30.0	78.7
Rural	4.3	35.5
Rural	13.1	51.6
Rural	20.1	62.6
Rural	28.4	81.7
Steady State	2.5	31.5
Steady State	28.8	77.9
Steady State	33.1	88.7
Steady State	14.6	52.2
DPG	14.1	53.2
DPG	28.1	86.2
DPG	17.3	57.0
DPG	29.0	93.6
DPG	6.1	36.0

The backpressure is plotted against soot mass for these tests below:

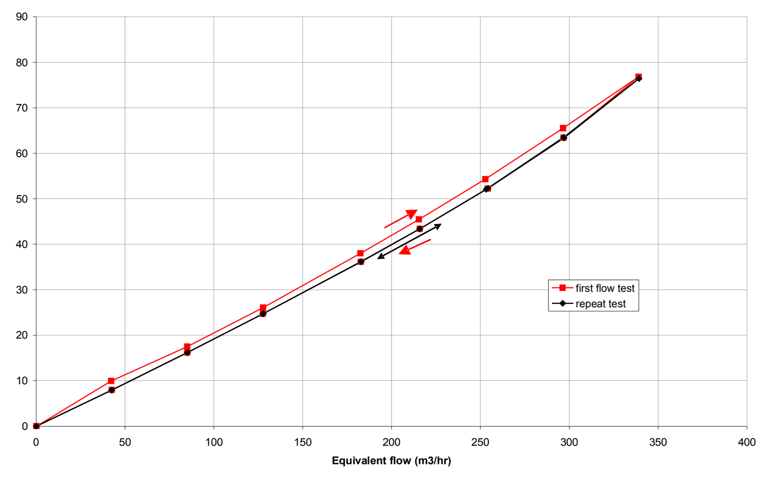


These results show very little difference between either the different operating conditions for the engine or for the engine and DPG. On the other hand, previously published[1] and also unpublished work has shown significant differences, particularly between soot deposited on a transient cycle and that produced at steady state on a dynamometer, where typically the steady state operation results in a higher backpressure for a given soot mass than the transient operation.

In order to investigate possible reasons for these results further investigations were performed.

Effect of High Flow on Soot Layer.

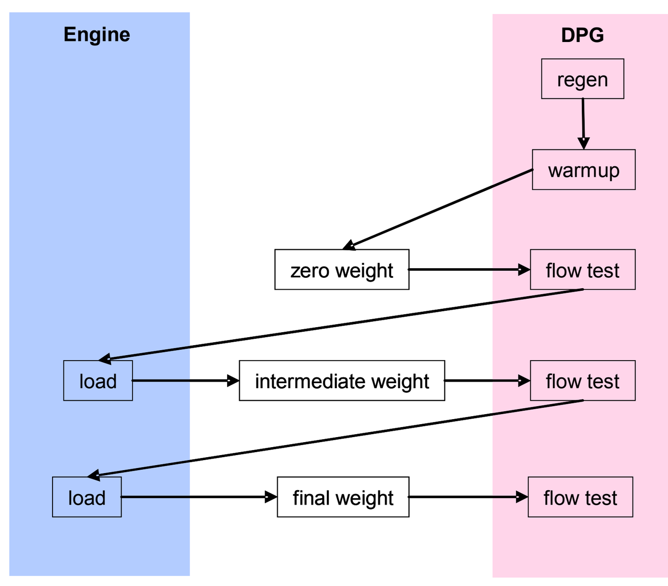
In the preliminary tests for this work, poor repeatability had been noted for flow tests made on loaded parts. The stabilisation phase was included in the loaded part tests above to eliminate this problem. When a loaded flow test was performed without this stabilisation phase, and then immediately repeated, the following results are observed:



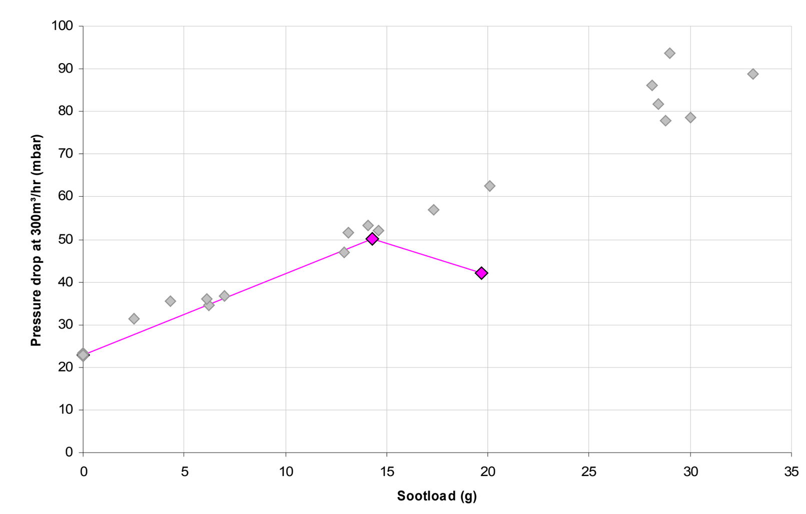
The backpressure measured in the first flow test (red) is higher as the flow scans up from zero than during the following dowscan. Successive flow tests, black, then repeat up and down the characteristic of the downscan. Inspecting the upscan characteristic, the shape, particularly at the high flows, is not the quadratic shape expected. This suggests that some permanent relaxation of the soot layer may occur at high loads.

Effect of Multistage Loading

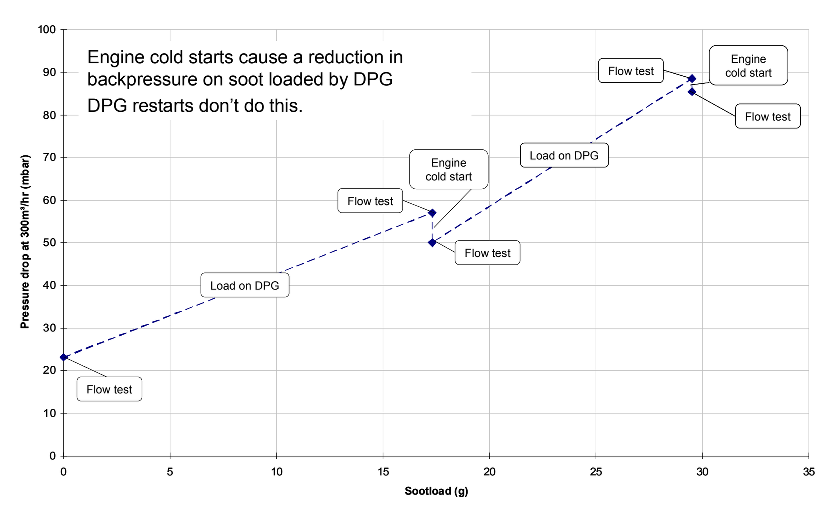
The above tests are all performed with a single stage load from empty. The effect of loading in several stages with cold starts on the engine between was investigated by the following test sequence:



When the part was loaded first to 14.3g and then on to a total load of 19.7g, the following backpressures were produced, compared with the single stage loading results in grey:

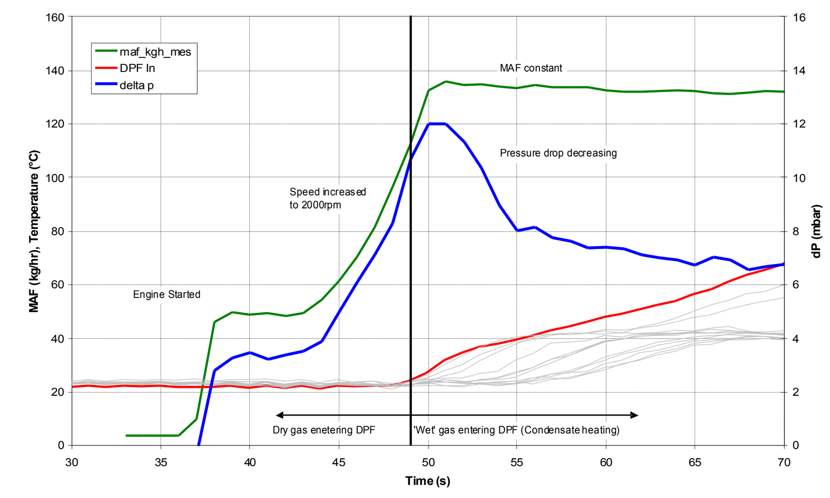


The additional loading phase actually produced a reduction in the backpressure. Repeating this test on the DPG did not produce this effect. To investigate whether the engine cold start or the engine soot was the key factor, a part was loaded on the DPG, then flow tested, transferred to the engine and cold started but then stopped before significant soot deposition, before repeating the flow test. This was then repeated:



The backpressure measured directly after the engine cold start was significantly lower than that measured just before. This behaviour was observed at 17.3 g and 29.5 g soot loads.

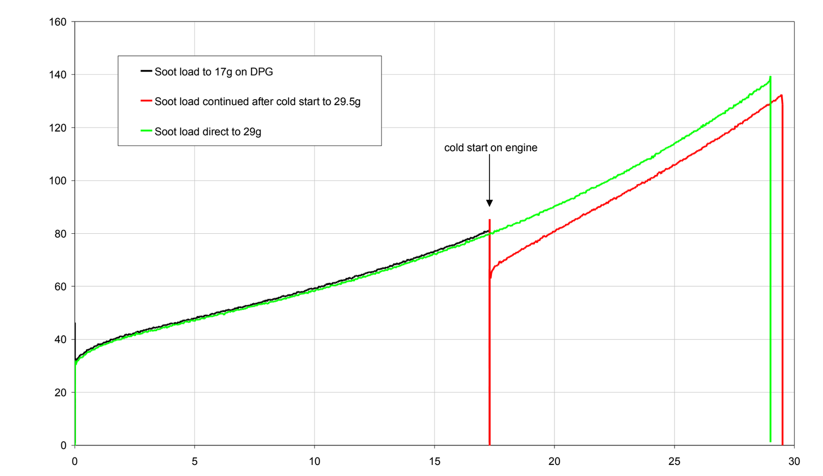
The conditions in the DPF during the engine cold start are shown below:



The grey lines show temperatures measured at a variety of different locations in the DPF during the cold start. The filter is initially at a temperature of ~25ºC. As the engine starts, the gas temperature rapidly rises (red), but the actual filter temperatures cluster around 40ºC for a while before rising any further. This is because water first condenses and then reevaporates from the filter in this period and this holds the temperature down to the dew point of the exhaust gas. This effect des not occur during a DPG start because the DPG operates at a higher AFR than the engine, and thus the dew point is lower, and the gas is non-condensing.

The measured pressure drop across the DPF is seen to reduce as this condensation – reevaporation process is occurring, despite the increase in the average DPF temperature which would otherwise be expected to produce a backpressure reduction.

These results suggest that the effect of water condensing on and reevaporating from the DPF is to produce a reduction in the filter backpressure. This effect is permanent, as shown by the continuing backpressure as this part is loaded on the DPG:



The backpressure never reaches the level produced by a single-stage load to an equivalent soot mass.

Conclusions

This work has shown that:

- Diesel Particulate Filters loaded non-stop, without cold starts, by a variety of different cycles, result in very similar soot mass : backpressure characteristics.
- The backpressure produced by soot generated by the DPG system is very similar to the engine soot.
- A number of effects which may be observed in real world application, such as high load conditions and cold starts may produce significant variation of the backpressure characteristic, and these effects are permanent (until regeneration).

This work looked only at a single engine, and an uncoated DPF. Further work is suggested to compare different engines and aftertreatment configurations, along with different operating conditions of the DPG.

Further work is taking place investigating other properties of the soot produced by the DPG, including it's reactivity and regeneration behaviour.

References

1. "A Standard Soot Generator for Diesel Particulate Filter Testing". T Hands et al. Emissions Reduction Conf. Aug 13-16 2007, Detroit
2. "The Effect of Different Ageing Conditions on Spatial Variations in Emissions across the Radius of a Close-coupled Aftertreatment System." C Burgess et al. SAE Paper 2005-01-1095
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