A Standard Diesel Combustion Aerosol Generator for DPF Testing

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Introduction

Testing the performance characteristics of Diesel Particulate Filters (DPFs) in the most representative way has up to now required the use of a engine dynamometer or rolling road to load the filters. This represents a major cost and may be impractical in a production environment. In addition, the particulate emission from a Diesel engine is often quite poorly repeatable, particularly in conditions of varying backpressure during the loading of the DPF.

Artificial aerosol generators based on a variety of techniques, such as liquid nebulisers or arc discharge, may be used for testing DPF performance, for example filtration efficiency. However, the behaviour of the DPF, in terms of backpressure, filtration efficiency and regeneration characteristics is strongly dependent on the soot layer and such laboratory aerosols cannot be used to produce a deposited layer representative of that produced by an engine.

Described here is generator for representative combustion particulates. The performance of the equipment is validated with backpressure versus soot load characteristic and filtration efficiency measurements. Particulate size distributions, Thermal-Gravimetric Analyses (TGA) of collected soot, and SEM of the deposited soot layer demonstrate characteristics similar to those from an engine.

Apparatus Design

To achieve representative soot chemistry, the generator is based on a Diesel fuelled burner. This operates with rich combustion subsequently quenched with excess air to achieve particulate production. In this work, the primary airflow was 13.2 m^3/hr, and fuel flow 1.7 m^3/hr. To maintain constant combustion conditions regardless of DPF backpressure, and to improve safety in the event of leaks, the burner runs at fixed pressure with the particulate laden gas drawn through the DPF by a downstream blower.

The pipe between the burner and the DPF is cooled by a variable speed fan in order to allow control of the DPF entry temperature (220ºC to 250ºC in this work). Downstream of the DPF, the gas passes through a cooler before reaching the blower. The blower is closed-loop controlled to achieve the desired total air flow, 144 m^3/hr for these tests. These conditions used here give a soot production rate of 2 g/hr, although the system is capable of higher rates.

Gas temperatures were monitored at DPF entry and exit, and the DPF backpressure was monitored. Accumulated soot mass on the DPF was established by the difference between the weight measured at 150°C for the bare DPF brick before and after a 650°C oven regeneration.

Particulate Characteristics

Measurements of the aerosol size spectrum were made with a Cambustion DMS500 with primary dilution of 4:1 at 50°C. The particulate size spectrum consists of a relatively stable accumulation mode around 100 nm, within the range observed for Diesel engines, and a more variable nucleation mode. The nucleation mode indicates the presence of significant volatile material in the aerosol. While there is some second to second variation in the particle emission, the average over longer periods is steady.

Scanning electron microscopy of the deposited soot layer in the DPF shows similar appearance of the deposited layer to that from diesel engine. The composition of the soot was studied by TGA and chemical analysis. TGA gave a composition of 26.5% volatile/organic and 73.5% carbon, compared with a control sample of Diesel engine soot of 27.4% and 72.2% respectively. The chemical analysis from samples taken from the DPG at different setpoints gave compositions ranging from 20.4% SOF : 67.4% elemental carbon : 12.2% sulphate to 27.6% SOF : 63.5% EC : 8.9% sulphate. These results show the particulate from the aerosol generator is similar to Diesel exhaust soot. The significant volatile fraction of the soot is important for behaviour representative of Diesel soot, but is unusual for synthetically generated aerosols.

Measurements of the aerosol generator conditions and output over a period of 7 hours (a typical duration to fully load a DPF at a similar rate to emission cycle conditions) shows very good stability after an initial warm up phase of a few minutes.

Fig 1: Soot Load : Backpressure Relationship

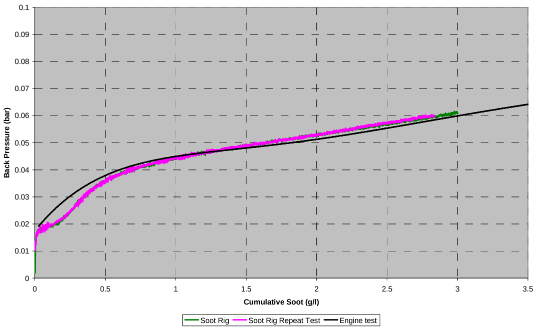
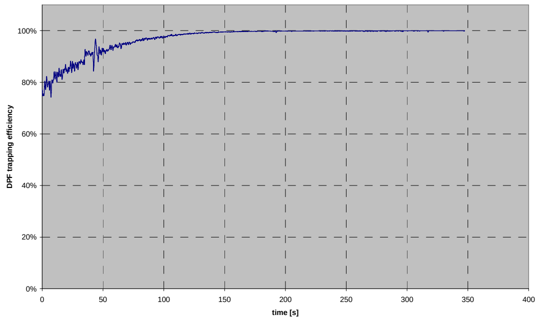


Fig 2: DPF Trapping Efficiency vs time.



Deposited Soot Behaviour

One important application for the aerosol generator is to confirm the relationship between soot load and backpressure for DPFs, both in production and in development. Therefore, it is important that this relationship measured using the aerosol generator is repeatable, and close to that measured with an engine. Figure 1 shows results for one DPF, with repeated runs on the aerosol generator and one measurement on the engine (a 2.0l unit injector turbodiesel). The engine was not as stable as the aerosol generator in this test, and therefore the engine loading pressure measurements were taken only at comparable conditions, with a polynomial fit to reduce the scatter.

The repeatability of the aerosol generator is very good, and close to the engine data after a slight difference in the pore filling phase: this is partly due to the data fitting process, and partly to differences in the initial loading state of the DPF (the aerosol generator runs were fully regenerated by an oven regeneration, whereas the engine data is after an engine regeneration which is less thorough).

Further measurements on multiple nominally identical DPF parts show similar good repeatability, with very slight differences attributable to piece-piece variation of the DPFs themselves. Measurements with different types of DPF have shown quite different soot load : backpressure characteristics, confirming the capability of aerosol generator measurements to distinguish between different the behaviour of different DPFs.

DPF Efficiency Measurement

Another important aspect of DPF performance is the particle trapping efficiency. Because this is strongly affected by the soot layer on the DPF, a stable and representative aerosol source is important for accurate measurement. Figure 2 shows the filtration efficiency measured continuously while loading a DPF from an initial lightly loaded condition. The filtration efficiency is measured using two Cambustion DMS500 analysers, upstream and downstream of the DPF.

The filtration efficiency rises from approximately 80% for the near-clean DPF to greater than 99.9% efficient by the end of the test.

Conclusions

A combustion aerosol generator based on the quenched combustion of Diesel has been demonstrated.

The physical properties of the aerosol formed are similar to those of Diesel engine generated particulates.

Backpressure vs soot load characteristics for a variety of DPF types are repeatable and representative of those measured with engine generated particulates.

DPF efficiency measurement using the aerosol generator and real-time particulate instrumentation has been demonstrated.

Future Work

Continuing research is in progress to further optimise the stability of the generated aerosol, broaden the range of conditions over which it can operate, and automate the procedure of testing Diesel Particulate Filters. It is hoped this equipment will be of wide application in research & development and production quality assurance applications.

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Introduction

Testing most of the performance characteristics of Diesel Particulate Filters (DPFs) in the most representative way has up to now required the use of a engine dynamometer or rolling road to load the filters. This represents a major cost and may be impractical in a production environment. In addition, the particulate emission from a Diesel engine is often quite poorly repeatable due to variations in conditions such as Exhaust Gas Recirculation (EGR) rate, particularly in conditions of varying backpressure during the loading of the DPF.

With the need for repeatable soot mass load versus backpressure characteristics for future regeneration control strategies to meet future stringent emissions standards, this is likely to increase in importance.

Artificial aerosol generators based on a variety of techniques, such as liquid nebulisers or arc discharge, may be used for testing DPF performance, for example filtration efficiency. However, the behaviour of the DPF, in terms of backpressure, filtration efficiency and regeneration characteristics is strongly dependent on the soot layer [1] and such laboratory aerosols cannot be used to produce a deposited layer representative of that produced by an engine.

With these restrictions in mind, we have set out to develop apparatus for the generation of particulates as close as possible to engine derived aerosol, in a stable and repeatable manner, and without the cost or infrastructure implications of a full engine test facility.

The performance of the equipment is validated with data from a variety of DPF substrates, coated and uncoated, including the backpressure versus soot load characteristic and filtration efficiency measurements. Repeatability over a number of tests is shown along with comparison with engine generated soot. Particulate size distributions and Thermal-Gravimetric Analyses (TGA) of collected soot demonstrate characteristics similar to those from an engine. Electron microscopy of the soot layer within a DPF shows similar deposition behaviour to engine-generated samples.

Apparatus Design

In order to give a similar chemical composition of the soot produced by the apparatus to Diesel exhaust soot, a Diesel fuelled burner is used. To maintain constant combustion conditions regardless of the DPF backpressure, the flow through the entire system is drawn by a vacuum blower on the output of the DPF (this also has a safety benefit as the entire system runs at a pressure slightly below ambient and so any leaks will be into the system, rather than of potentially harmful gas into the surroundings).

The burner is an ambient pressure swirl-type. The operating conditions of the burner are optimised to produce particulates similar to those in Diesel exhaust. This requires a rich primary combustion followed by dilution and quenching by a secondary air flow. The burner is located in a sealed enclosure with the total primary + secondary airflow drawn in via a flowmeter. The primary air is drawn from the sealed enclosure by a fan in the burner body itself, and is mixed with the fuel and ignited. The secondary air is introduced around the periphery of the flame.

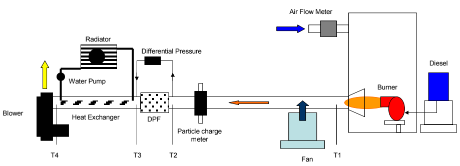
Between the enclosure and the DPF, the combusted gas passes through a 100 mm diameter tube finned on the outside and cooled by a variable speed fan to control the DPF entry temperature. An industrial stack monitoring type particulate emissions probe (PCME Ltd) is located just upstream of the DPF to indicate the particulate level.

The DPF monolith is held in a demountable can to allow easy removal for weighing. Downstream of the DPF, the gas passes through an air:water heat exchanger to reduce the temperature. It is then extracted from the system by a variable speed blower. The speed of the blower is close-loop controlled to maintain the desired primary + secondary airflow.

Monitoring for the gas temperatures at burner exit and DPF entry and exit is provided by thermocouples, along with flow rate and DPF backpresssure.

A schematic layout of the system is shown below:

Fig 1: Combustion Aerosol Generator Layout



Operation

Operating conditions of the aerosol generator were selected to closely reproduce the soot produced by a light duty passenger car Diesel engine at conditions approximating those encountered on the legislated emissions cycles. The overall flow rate used in this work is 144 m^3/hr, with a primary airflow of 13.2 m^3/hr and fuel flow 1.7 kg/hr. The DPF entry temperature was between 220ºC and 250ºC.

The soot production rate was measured from the change in mass of the DPF monolith over a period of time. To establish the mass flow, soot is accumulated on a completely clean DPF for a period (typically several hours). The DPF monolith is removed from its housing, heated in an oven to 150ºC to remove water and is weighed. It is then returned to the oven and taken up to 650ºC until fully regenerated (accumulated soot oxidised) and then reweighed at 150ºC. The difference between the two weighings is taken to be the mass of soot accumulated.

The conditions used in this work produce a soot rate of 2 g/hr.

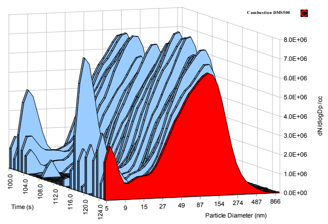
For comparison, DPFs were also loaded with an engine on a dynamometer. The engine is a 1.9 l unit injector turbodiesel. The engine was run on a repetitive cycle with mean output and deposition conditions similar to the aerosol generator operation. Some of the engine based tests were initiated with DPFs which had been regenerated by operating the engine at high temperature exhaust conditions, whereas all aerosol generator tests were conducted with oven regenerated DPFs.

Particulate Characteristics

Measurements of the aerosol size spectrum have been made with a Cambustion DMS500. These were made using the built-in dilution system of the DMS500 with 4:1 primary dilution at 50ºC. This was selected to promote the formation of a nucleation mode if the precursors were present, as representative levels of these are an important aspect of the generator's similarity to a Diesel engine.

The particle size spectrum and second by second variation produced by the aerosol generator are shown in figure 2.

Fig 2: Dynamic Combustion Aerosol Generator Spectrum

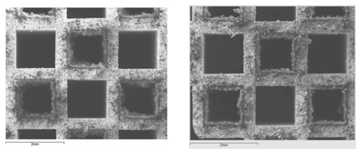


The particulate size spectrum consists of a relatively stable accumulation mode around 100 nm and, with this dilution, a more variable nucleation mode. The accumulation mode size is within the range observed for Diesel engines. The nucleation mode indicates the presence of significant volatile material in the aerosol. While there is some second to second variation in the particle emission, the level over longer periods is rather steady.

Variation of the generator setpoints, particularly of the primary air:fuel ratio produce a range of particulate size and concentration, but these conditions are those used for the testing reported here.

The soot layer deposited on the DPF was inspected via low resolution scanning electron microscopy. Figure 3 shows the comparison between the layers deposited by the aerosol generator and the engine. The images are from a sectioned DPF, 100 mm from the entry face.

Fig 3: Deposited Soot Layer. Generator to Engine Comparison

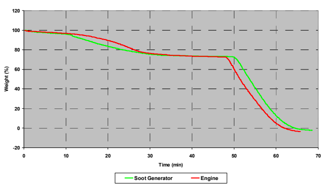


Combustion aerosol generator — Engine

The thickness and morphology of the soot layers appears to be similar.

The "wetness" of soot is known to affect its behaviour in a DPF. In order to establish the chemical content of the soot produced, samples collected on filter paper from the aerosol generator and the engine were analysed by TGA.

Fig 4: TGA analysis of collected soot

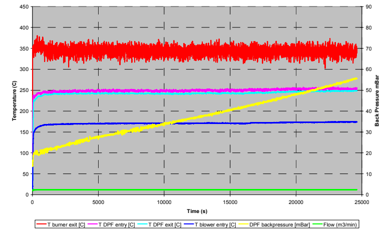


Aerosol Generator	
26.5%	volatile / organic
73.5%	carbon
Engine	
27.4%	volatile / organic
72.6 %	carbon

Laboratory chemical analysis from further samples taken from the DPG at different setpoints gave compositions ranging from 20.4% SOF : 67.4% elemental carbon : 12.2% sulphate to 27.6% SOF : 63.5% EC : 8.9% sulphate. These results place the particulate from the soot generator in the same range as Diesel exhaust soot. The significant volatile component of the soot is distinct from the composition of many other synthetically generated aerosols but is consistent with the observation of a nucleation mode formation above, and is important for representative behaviour of the soot layer.

Stability of the generator over time is shown by the data for backpressure, flow rate and temperatures during a 7 hour test:

Fig 5: Aerosol Generator Stability During Run.



The stability of the loading conditions produced by the aerosol generator is very good after a short warming up period. The uncoated filter used in this test produces a linear relation between soot load and backpressure, after the initial pore filling phase.

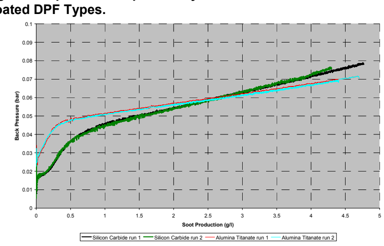
Deposited Soot Behaviour

For engine control systems using DPF backpressure as an input to the regeneration strategy, the piece-to-piece variation in DPFs must be tightly controlled. Therefore, it is important that backpressure vs. soot load characteristics measured with the soot generator are repeatable and similar to those obtained with engine generated particulates.

In the following results, the backpressure is plotted against cumulative soot produced by the generator inferred from the terminal weighing of the DPF described above — assuming constant soot output (verified with a DMS500). This is normalised by DPF volume.

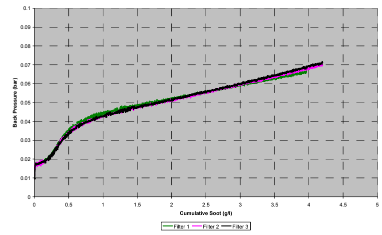
Figure 5 shows the repeatability of the aerosol generator between runs for two different filters: the repeatability of the equipment is clearly sufficient to discriminate between the two loading characteristics.

Fig 5: Backpressure Repeatability and Discrimination of Different Coated DPF Types.



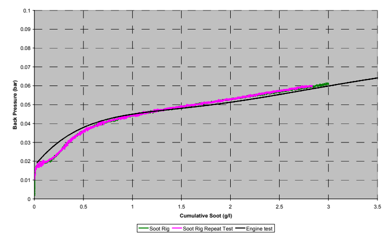
Measurement of the backpressure during loading of several nominally identical parts shows slight piece to piece variation:

Fig 6: Piece to Piece Variation, Coated SiC DPFs



Correlation of the backpressure vs. soot load characteristic with that from engine produced soot is shown below. The engine condition is less stable than that achievable with the soot generator, so the backpressure data from the engine has been sampled only at times where the temperature and flow rate are comparable, and a polynomial fit applied to reduce the scatter.

Fig 7: Comparison of Δp : Soot Load Characteristic with Engine.

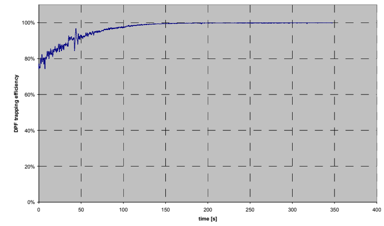


The repeatability of the measurements with the aerosol generator is very good, and both are close to the engine condition. The small difference at the start is partly accounted for by the data processing necessary for the engine data, and partly due to different regeneration procedures for the engine and aerosol generator parts prior to the run.

DPF Efficiency Measurement

Another important aspect of DPF performance which requires a stable, representative aerosol source for accurate measurement is the filtration efficiency. As reported before [1], this is a strong function of the soot layer on the DPF. Figure 8 shows the filtration efficiency calculated continuously while continuing to load a DPF which is initially very lightly loaded. The filtration efficiency is measured using two Cambustion DMS500 analysers, upstream and downstream of the DPF, measuring the real-time particulate mass concentration of the soot accumulation mode particles only.

Fig 8: DPF Efficiency, Loaded from Near-Clean



The filtration efficiency rises from approximately 80% for the near-clean DPF to greater than 99.9% efficient by the end of the test.

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References

[1] 'Real time Diesel particulate filter efficiency and mass measurements from spectral data'. Hands T, Nickolaus C, Symonds J. Proc. AGM AAAR, October 2005.