



DMS500 MkII

Fast Particulate Analyzer

Application Note: DMS 05v02

Diesel Particulate Filter Measurement with the DMS500

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The Cambustion DMS500 with integrated two stage dilution system, wide dynamic range and heated sample line option is uniquely suited for a variety of Diesel Particulate Filter applications including:

- Efficiency measurement
- DPF loading and regeneration studies
- Faulty filter detection

This Application Note describes how to conduct such measurements with the DMS500 and the features to expect in the data obtained. It is equally relevant to DPF (alias FAP or DPT, Diesel Particulate Trap) and CRT (Continuously Regenerating Trap) systems fitted to either light or heavy duty Diesel engines and tested on vehicle or engine dynamometer.

These applications require measurement both upstream and downstream of the DPF so the sample must be drawn direct from the exhaust system rather than from a dilution tunnel. This calls for a very wide dynamic range and immunity to variations in temperature, pressure and humidity which exist at the sample point. To conduct these measurements during standard emissions test cycles a fast time response is necessary to resolve events associated with transient conditions.

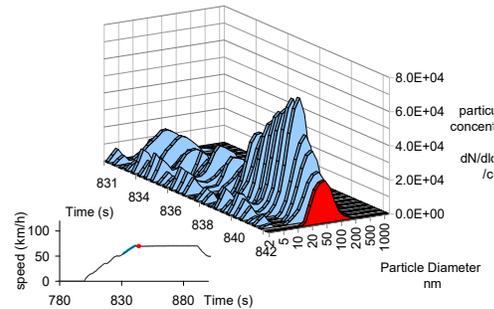


Figure 1: Particulate spectrum downstream of DPF measured with the DMS500: accumulation mode breakthrough occurs at high space velocity during high speed acceleration.

Recommended Instrumentation

Cambustion DMS500 with integrated two-stage dilution system (Figure 2).

- Allows direct measurement from the untreated exhaust gas without requiring any other sampling equipment; this is more convenient than external dilution systems because:
 - the integrated dilution system is controlled from the DMS500 interface
 - concentration measurements are automatically corrected by the DMS for the dilution ratio applied.
- The DMS500 time response is faster than any other ultrafine particle instrument available.
 - allows accurate resolution of transient events and accurate time alignment with mass flow data for modal analysis.
- The DMS500 measures the whole particle size spectrum allowing the carbon accumulation mode to be distinguished from the liquid nucleation mode particles. It also allows real-time weighting of the particle concentration by diameter to correlate with conventional mass measurements.
- Unique new software (see app. note DMS06) automatically discriminates between the nucleation and accumulation modes and can even output particle mass or number in any mode in real-time (app. note DMS01 version 2).
- With two (or three) gain ranges the DMS500 has a wide dynamic range allowing measurement of low concentration carbon accumulation mode particles in the presence of a high concentration nucleation mode.

The *remote sample cyclone* supplied with the DMS500 (also integrated with the optional heated sample line) should be used as this improves time response of measurements and reduces

condensation and particle accumulation in the sample line. This incorporates the annular type low ratio primary diluter.

The *optional heated sample line* is recommended. Along with the heated operation of the DMS500, this allows measurement of humid exhaust gas undiluted without the risk of condensation. This may be useful downstream of the DPF where particulate concentration can be very low.

The use of *two instruments for simultaneous upstream and downstream measurements*. As well as substantially reducing development time, this improves the accuracy of DPF efficiency measurements significantly because the repeatability of engine-out particle emissions is often poor: due particularly to variations in delivered EGR and ambient conditions.

Measurement Upstream of a DPF

Upstream of the DPF the exhaust may be hot, is subject to rapid pressure fluctuations associated with varying speed and load and has high particulate concentrations. It is recommended to use the remote cyclone connected to a compression fitting in the exhaust by a length of $\frac{1}{4}$ inch steel tube. This tube should be as short as possible to limit artefacts caused by the cold pipe and to preserve time response, as the flow through this tube is relatively low (equal to the DMS500 sample flow divided by the primary dilution ratio). For the particle sizes of interest isokinetic sampling is not critical although a scarfed end on the sample tube facing the flow and protruding into the exhaust beyond the boundary layer is best.

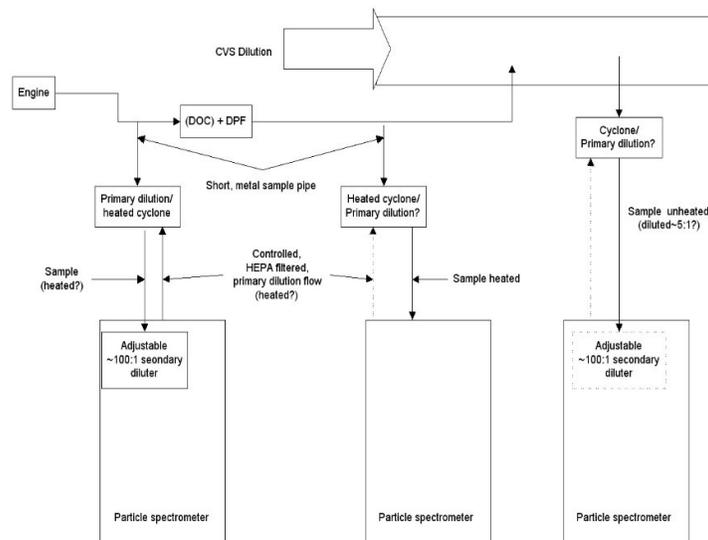


Figure 2: Recommended DPF sampling configurations, pre- and post-DPF and in CVS dilution tunnel

The sample orifice should be mounted in the heated sample line or the unheated remote cyclone: this will run the sample line at DMS column pressure, improving the time response and reducing condensation and losses. The DMS sample orifice has a large pressure drop across it, which reduces the sensitivity to transient sample pressure fluctuations compared with instruments running close to atmospheric pressure.

The remote cyclone incorporates the primary diluter. A primary dilution ratio of 4 is recommended: this is selected in the DMS500 interface and, with dilution correction enabled, is automatically accounted for in the particulate concentration calculations. Use of the primary dilution feature requires a supply of oil free compressed air to the DMS500; filtration of this air is built in to the instrument. This dilution reduces the sample drawn from the exhaust, prevents condensation in the sample line and reduces the sample temperature with minimal particle losses. If the heated line is used the sample line temperature can be checked on the DMS interface (it is displayed on the 'info' dialogue as 'sample

temperature'): if this exceeds the maximum 150°C allowed for the flexible line, it can be reduced by increasing the length of steel tube between the sampling point in the exhaust and the remote cyclone or increasing the primary dilution.

To minimise instrument cleaning it is recommended to operate the DMS500 in high gain and, on average, within the green band on the dynamic range indicator on the main interface screen. Continued operation above these levels risks build up of deposits in the column which may cause spurious signals, while lower levels compromise signal to noise ratio. The secondary dilution ratio should be adjusted to obtain this signal level: the dilution is automatically accounted for if 'dilution correction' is selected. For a light duty Diesel engine a secondary dilution ratio of 200 is typical; for a modern heavy duty Diesel this may be several times lower. The dilution ratio may be varied while logging: it is continuously measured and the current value accounted for in the instrument output (if dilution correction is on): however, some transient errors may be observed.

If a heated sample line is fitted it is recommended to operate this at around 60°C, as a further insurance against condensation and to reduce any nucleation mode formation (which upstream of a DPF is not representative of tailpipe emissions and is confusing), or to the same temperature as the DMS sampling downstream of the DPF, for consistency of measurement conditions.

Measurement Downstream of a DPF

The sampling point into the remote cyclone should be mounted far enough downstream of the filter that the exhaust is well mixed: typically 10 pipe diameters is sufficient. To prevent condensation in the line, either a primary dilution ratio of around 4 is required, or the sample line should be heated to at least 60°C and the column to around 40°C. Thus for highly efficient filters, the heated sample line allows lower dilution ratios and hence improved sensitivity. The minimum length of unheated tube between the exhaust and remote cyclone should be used to ensure (with the primary dilution ratio selected) that the sample temperature reading remains below 150°C.

Generally relatively little dilution is required to maintain the average signal level in the green region of the dynamic range scale at high gain. This may be a total (primary × secondary) dilution of around 40 for a passenger car DPF, down to no dilution for a highly efficient filter. However, it is important to be aware that post-filter concentrations may vary more widely than pre-filter. Leaks around the filter when the support mat is cold, poor efficiency of completely clean filters, penetration at high space velocities and breakthrough during DPF regeneration may all produce relatively short lived but high accumulation mode concentrations which should be considered when setting the dilution.

Nucleation mode concentrations downstream of the filter may also be extremely high (these particles are formed from precursors which pass through the filter in the gas phase and then condense either in cold exhaust components or during the dilution process). In most investigations of DPF performance the nucleation mode is not of primary interest and the recommended heated, low pressure (and hence short residence time) operation of the sample line with low primary dilution ratios should minimise the nucleation mode formation: this makes it easier to measure the accumulation mode particles of interest. However, under some conditions high nucleation mode concentrations may still be produced. The custom gain range setting in the DMS500 can be used to optimise the measurement of the accumulation mode in this case: the custom gain range should be set to low gain on the ring electrometers 1 to 8, and high on the remainder. The varying gain across the size range is automatically handled by the DMS data processing, and this better matches the available dynamic range to the concentrations occurring. High concentrations of nucleation mode particulates are less critical for column cleaning, as these particles are liquid and very small.

In some applications it may be desired to produce a nucleation mode representative of that formed in the environment. In this case a primary dilution ratio of 4, with the sample line unheated and the sample flow restrictor mounted in the DMS500 main unit (thus running the sample line at ambient pressure and increasing the residence time) will produce nucleation modes closer to those seen on the road. However, the increased residence time inevitably slows the time response of the overall measurement. For more advice on nucleation mode formation please contact Cambustion.

Measurement in the Dilution Tunnel

Measurement of the tailpipe emissions may also be made from a CVS dilution tunnel if available: this is particularly useful to provide second by second emissions data comparable with the conventional filter paper measurement. The dilution provided by the tunnel avoids the risk of condensation, and so neither the heated line nor primary dilution is required. For best time response and reduced fouling of the sample line, the remote cyclone with sample flow restrictor should be mounted close to the dilution tunnel.

With a particulate filter the concentrations in the dilution tunnel are unlikely to be high enough to require use of the secondary diluter (it typically is required for unfiltered engines).

The dilution provided in the tunnel will generally result in the formation of high concentrations of nucleation mode particles. Therefore it may be useful to use the 'custom' gain range setting of the DMS500, with this configured for low gain on ring electrometers 1 to 8 and high gain otherwise, as discussed for post-filter measurements.

Processing and Interpretation of Data

With dilution correction active the concentration outputs from the DMS directly correspond to the concentration in the exhaust and so no post-processing is required. If a test cell datalogging system is in use one of the DMS analogue outputs may be connected to it, set to correspond to the total number in a size range from approximately 25nm to 200nm: this will exclude most nucleation mode particles and allow fast evaluation of the particulate filter efficiency.

New software from Cambustion (see app. note DMS06) can automatically discriminate in real-time between nucleation and accumulation modes even when they partially overlap, and even calculates particle mass in each mode (see app. note DMS01 version 2), providing a signal proportional to each as analogue outputs which can be logged to existing test cell facilities. DMS data files can also be post-processed with an Excel version of the tool.

DPF efficiency is easily calculated from the simple ratio of the concentrations measured directly in the exhaust (i.e. not from a dilution tunnel) upstream and downstream of the filter. For the most accurate real-time calculation of the filtration efficiency when simultaneous pre- and post- filter measurements are available, the pre-filter measurements should be delayed by the residence time in the DPF for comparison with the post-filter concentrations.

Efficiency calculations are especially sensitive to noise on the post-filter concentrations: for accurate calculations the average post-filter concentration must be significantly higher than the noise in the measurements. The averaging in the DMS500 interface should be selected to ensure this: averaging the concentrations logged to the datafile is not as effective due to effective rectification of the noise that takes place in the data processing.

To retrospectively increase the sample averaging, the DMS Data Processing tools for Excel can be used to average the logged electrometer currents and then re-invert the averaged currents.

DPF trapping efficiency can vary widely with operating conditions, filter condition and between different filters. Some absolutely clean filters may show trapping efficiency as little as 90%, although this will rapidly increase as a soot layer builds up, while other filters may be more than 99.99% effective. Typically the worst filter effectiveness is seen at very high flow rates, associated with high speed and load conditions. Leaks around the filter substrate, through the support mat, may be dependent on temperature: sometimes these are only seen with a cold system before they are closed by thermal expansion. Leaking filters may show up most at low load, as the flow rate through a leak is often proportional to the square root of the pressure drop whereas that of the filter is linear with pressure, so the leak is proportionally more significant at low exhaust flows. Due to these factors, emissions which appear very low accumulated over a whole test cycle are sometimes easily detected by real-time measurement with the DMS500.

Apparent negative DPF efficiency is often seen due to nucleation mode formation downstream of the filter. In this case, the measurement of the whole size spectrum by the DMS500 allows these particles to be easily distinguished from those in the accumulation mode, which is not possible with a simple total particle count.

While direct calculation of filter efficiency is possible from the DMS concentration measurement, calculation of cycle emissions from measurements made directly in the exhaust requires multiplication by instantaneous exhaust mass flow (unlike measurements made in the CVS system, which directly relate to total emissions). This is easily performed in a data analysis package or spreadsheet if an exhaust flow signal is available from the engine test facility (typically either from the engine control system or an exhaust flow transducer). If this is desired, it may be most convenient to log this signal to one of the DMS500 analogue inputs so that the data is available synchronous with the particulate measurements in the DMS datafile.

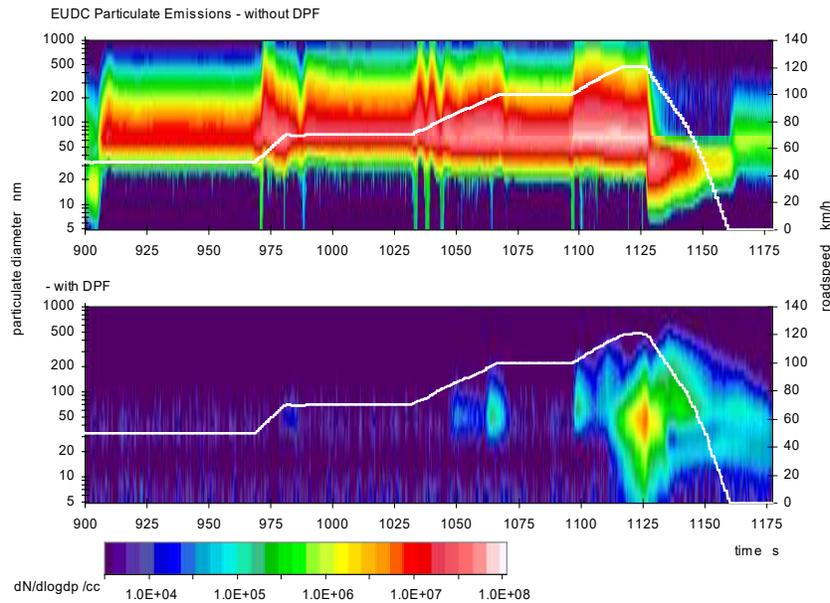


Figure 3: Comparison of emissions at end of European Extra-Urban Drive Cycle with and without DPF

Figure 3 above shows a comparison of the emissions produced upstream and downstream of a Diesel Particulate Filter in the final 300s of the European Extra-Urban Drive Cycle, which illustrates some of the effects discussed above. Without the DPF the particulates show the typical variation between accumulation and nucleation mode emissions during loaded and no-load conditions respectively. Downstream of the filter the particulate concentration is generally more than 3 orders of magnitude lower than that in the raw exhaust: at low exhaust flows this filter is more than 99.9% efficient. However, during the accelerations around 1060 seconds and 1100 seconds, breakthrough of the accumulation mode is visible.

After 1115s post-DPF, large nucleation mode production is seen (these measurements were made with cold primary dilution): this is often observed as the catalyst or filter substrates exceed a temperature of around 400°C which causes sulphur or hydrocarbon material that is deposited on them throughout the lower temperature part of the cycle to be released. This can produce very large concentrations of these materials in the exhaust for several tens of seconds which produces rather larger nucleation mode particles than are normally seen, although they are still slightly smaller than the accumulation mode here. Undiluted or with heated primary dilution, the formation of this nucleation mode can be reduced which is more convenient for investigation of the accumulation mode filtration.

We now turn to an example of using two DMS500s simultaneously to measure DPF efficiency.^{1,2} A 4 cylinder common rail Diesel engine with DPF, running on a transient engine dynamometer was instrumented with two DMS500 systems. Several different DPF samples were investigated as follows:

- DPF cleaned by regeneration at ~550°C for 600s followed by engine soak to 25°C
- New European drive cycle (#1)
- Trap loading cycle to put ~ 2g of soot onto the trap substrate (steady state)
- New European drive cycle (#2)

Standard filter paper measurements were made in the CVS tunnel.

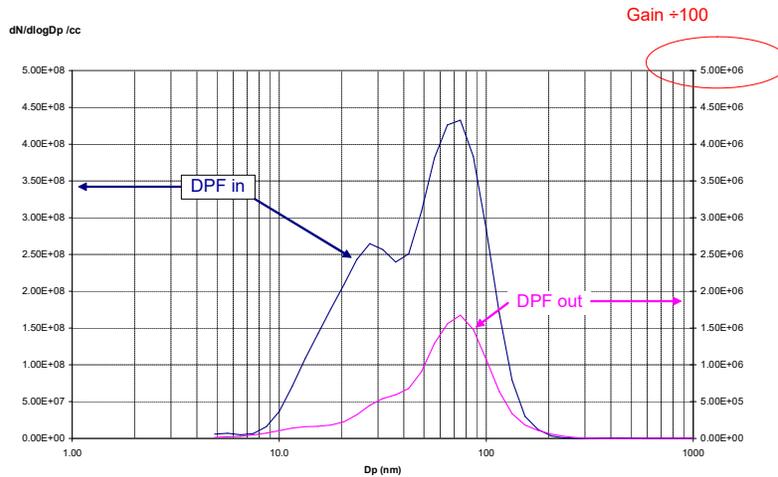


Figure 4

Figure 4 above shows the averaged aerosol spectra corresponding to the gas entering the DPF and that exiting the DPF. The data is typical of all the DPFs tested and shows a characteristic peak in accumulation mode diameter of around 75nm. Note that all data have been corrected for dilution ratio. The nucleation mode apparent on the feed-gas measurement is significantly reduced at the tailpipe.

For the results following, the spectral data is summarised by looking at the dN/dlogDp value (corresponding to number concentration) at 75nm. The drive-cycle on the transient dynamometer is computer controlled and therefore the test to test repeatability in engine-out aerosol is expected to be good. The transient spectral summary data corresponding to the amount of aerosol with diameter 75nm (representing the solid exhaust material) shows good repeatability over the 6 tests plotted on Figure 5.

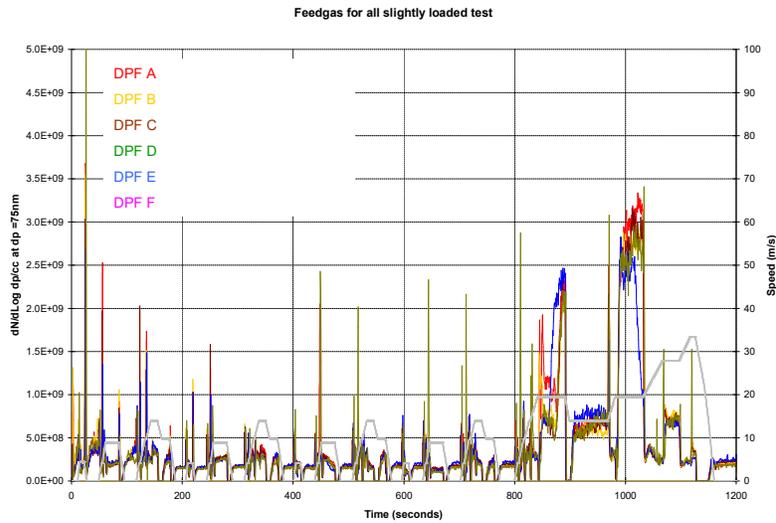


Figure 5

Figure 6 shows the summary of the spectral data corresponding to the 75nm (solid material) for 6 different DPFs for the first drive cycle following a trap cleaning cycle. Note that the Y scale has been reduced to give a gain factor of 10 compared with the previous figure.

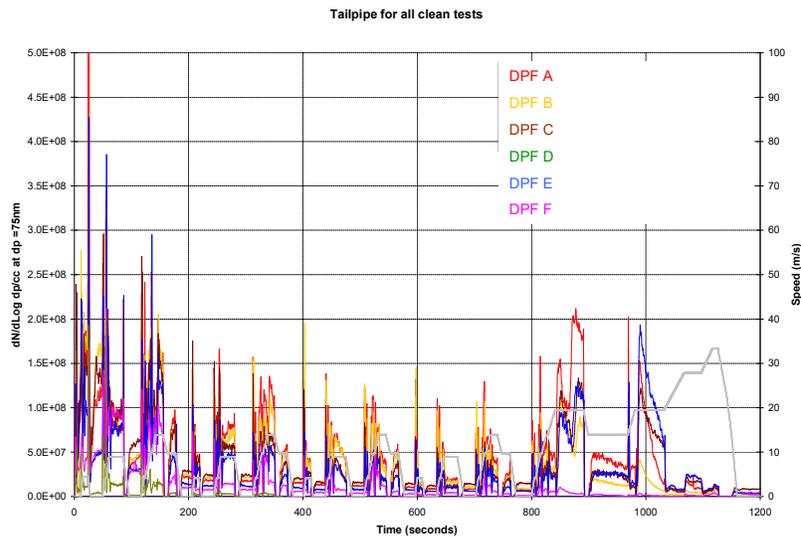


Figure 6

The data show different performance in transmission of the 75nm aerosol between the various DPFs.

Figure 7 shows the summary of the spectral data corresponding to the 75nm (solid material) for 6 different DPFs for the drive cycle following the first drive cycle shown above and a further trap loading cycle (described above). Note that the Y scale has been further reduced by a second factor of 10 to give a gain factor of 100 compared with the feedgas data.

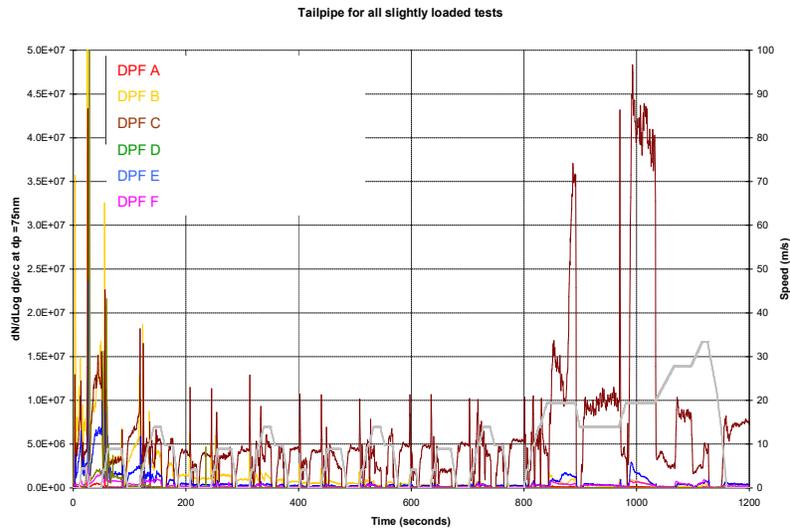


Figure 7

The data indicates that the trapping ability for all the DPFs tested improves significantly after a relatively small amount of trap loading. However, some traps are clearly much better than others. Comparison with the 'clean' DPF data shows that trap performance improvement with loading is not the same for all traps. The data for trap C indicates that there may be a leak with this DPF.

Figure 8 shows the engine-out and tailpipe aerosol at 75nm for DPF A when it is loaded with ~ 2g of soot (note that there is a 1000x gain difference between the y axes).

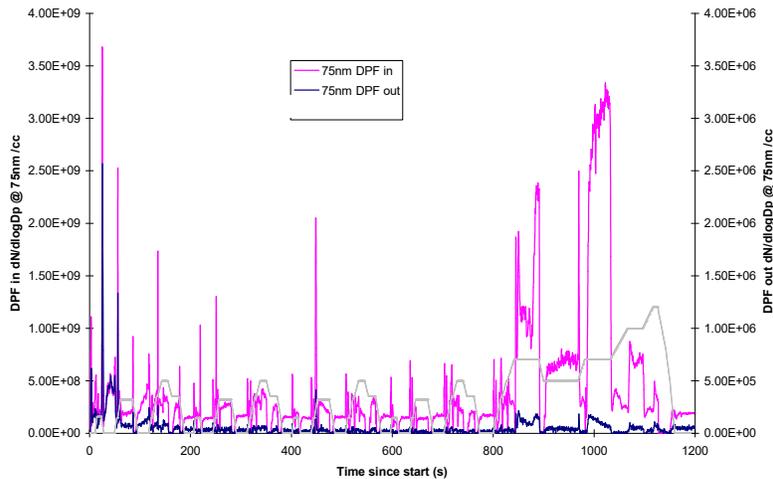


Figure 8

We can define an efficiency for the DPF as follows:

$$\eta = 100 \times \left(\frac{\text{DPF in} - \text{DPF out}}{\text{DPF in}} \right)$$

Using this formula we can produce a filtration efficiency (based on number of particles at 75nm) which is shown in Figure 9. This figure contains data for DPF A following a cleaning cycle (dark blue line) and following a soot loading cycle (pink line).

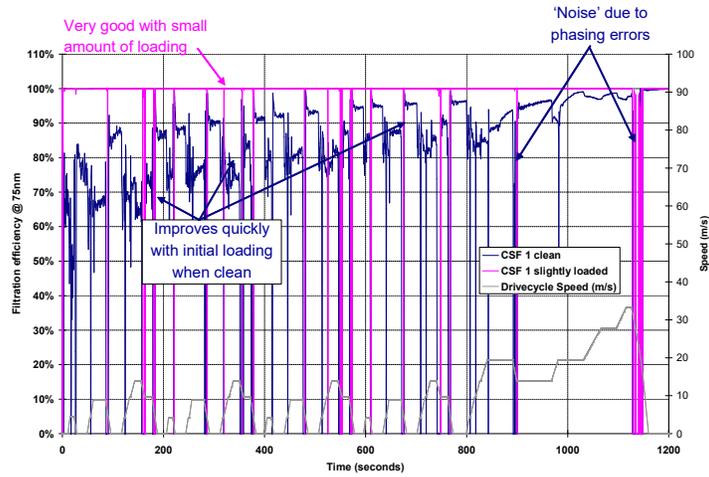


Figure 9

Note that phasing differences associated with the highly transient nature of the data leads to the 'noise' on the efficiency plots. The efficiency plots clearly show that there is a significant improvement in filtration efficiency after 2g of soot loading for this DPF. Further, the efficiencies for both the clean and the loaded trap are observed to generally improve throughout the drive cycle. This effect is also demonstrated in data corresponding to DPF G shown in Figure 10 below.

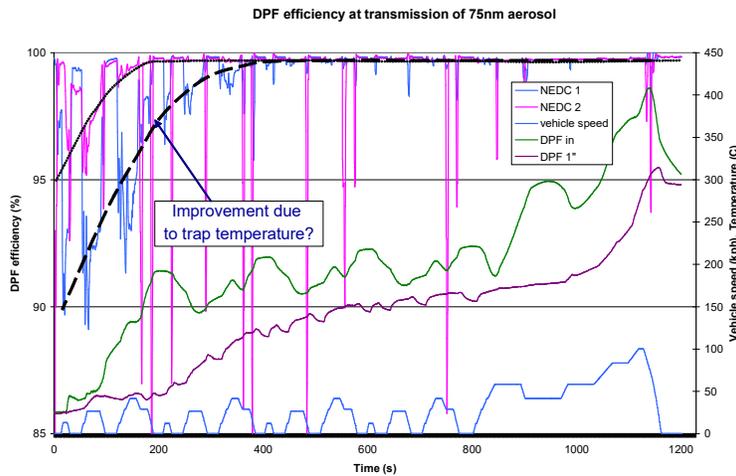


Figure 10

The data in the final figure indicates that the efficiency of DPF G improves with the loading of ~2g of soot, but significantly less than that for DPF A. All traps show a general efficiency improvement over the NEDC. The trajectory of this improvement is broadly consistent with the exhaust temperatures measured at the DPF inlet and 1" into the DPF. This apparent improvement in filter performance as the trap warms up may be due to the increase in diffusion with temperature (although the lower density at high temperature reduces the residence time).

Summary

The DMS500 is proven in measurements of DPF or CRT performance using:

Upstream of the DPF – DMS500 with remote cyclone, integrated two stage dilution and preferably heated sample line, for:

- prevention of condensation in instrument and sample lines
- low sample flow extracted from aftertreatment system

Downstream of the DPF – DMS500 with heated sample line or primary dilution and optional secondary dilution, with differential gain for nucleation and accumulation particles:

- large dynamic range of measurement for typical low accumulation mode concentrations with transient breakthrough and nucleation mode formation.
- prevention of condensation
- second by second measurement of DPF efficiency

CVS dilution tunnel – DMS500 with built-in high ratio diluter for:

- correlation with whole-cycle filter mass measurements
- discrimination of nucleation and accumulation mode particulates.

Data processing – calculation of DPF efficiency, integration with mass flow for total emission calculation from raw sampled measurements, real-time analogue output to other test instrumentation. Automatic discrimination of nucleation and accumulation modes, real-time mass calculation; mass or number in each mode can be sent to analogue outputs.

These conditions are summarised in the table below:

	<i>Upstream of DPF – direct</i>	<i>Downstream of DPF - Direct</i>	<i>From CVS tunnel (with DPF)</i>	<i>From CVS tunnel (without DPF)</i>
<i>Hardware</i>				
<i>DMS500</i>	•	•	•	•
<i>Remote cyclone</i>	•	•	• (recommended)	• (recommended)
<i>Heated sample line</i>	• (recommended)	• (recommended)		
<i>Dilution</i>				
<i>Primary</i>	4	0 – 4	None (except CVS)	None (except CVS)
<i>Secondary</i>	50 – 200	0 – 20	none	50-500
<i>Total</i>	200 – 1000	0 – 40	none	50-500
<i>Gain range</i>				
<i>High</i>	•			•
<i>Custom</i>		• (≤8 low, >8 high)	• (≤8 low, >8 high)	
<i>Applications</i>	DPF efficiency measurement		Filter mass correlation	
	DPF mass loading	DPF failure diagnosis		Engine calibration
	Engine calibration			
<i>Key advantages of DMS</i>	low sample flow	high dynamic range		
	raw sampling capability			
	fastest time response available			
	automatic mode discrimination & mass calculation			
	easy integration with existing test cell facilities and data logging systems			

For any further information and advice, please contact Cambustion, www.cambustion.com

¹ *Diesel Particulate Filter Performance evaluation with Fast Aerosol Spectrometers* N. Collings, T. Hands, G. Inman, *16th Regional Conference of Clean Air and Environment in Asian Pacific Area*, Japan **2005**

² *Real-Time Diesel Particulate Filter Efficiency and Mass Measurement From Spectral Data*. T. Hands, C. Nickolaus, J. Symonds, *American Association of Aerosol Research*, Austin, USA **2005**