Real-time Mass Concentrations from Measured Size Distributions

Introduction

Particle mass (PM) has been long established as a metric for legislative measurements of particle emissions from engines, and remains in force in many countries.

The relatively recent addition of Particle Number (PN) legislation in some markets, with a different measurement technique, provide an additional parameter to optimise for.

PM and PN measurements do not demonstrate a direct correlation unless the size of the particles (and hence mass per particle) is fixed. This is not the case for either Diesel or gasoline engines, where different local AFR during varying operating conditions produces different sized soot agglomerates.

DMS500

The DMS500 (since 2003) measures the particle size/number distribution in an engine exhaust, at up to 10Hz. An integrated (software and hardware) dilution system allows measurements of raw exhaust to be made, although CVS sampling is also possible. The total number concentration (N/cc) is calculated from the size distribution in real-time.

Given a size/number distribution, it is desirable to calculate in real-time a mass concentration. This may be done providing assumptions are available about the density and morphology of the soot particles, which allows the diameter of a soot particle to be related to its volume and hence mass. Note that soot particles are not spherical, and therefore a calibration made specifically with soot is used to allow accurate measurement.

Methodology

Given a size/number distribution, it can be reweighted to a volume distribution by the simple method of calculating the volume contributed by a particle at each size, see Figure 1.

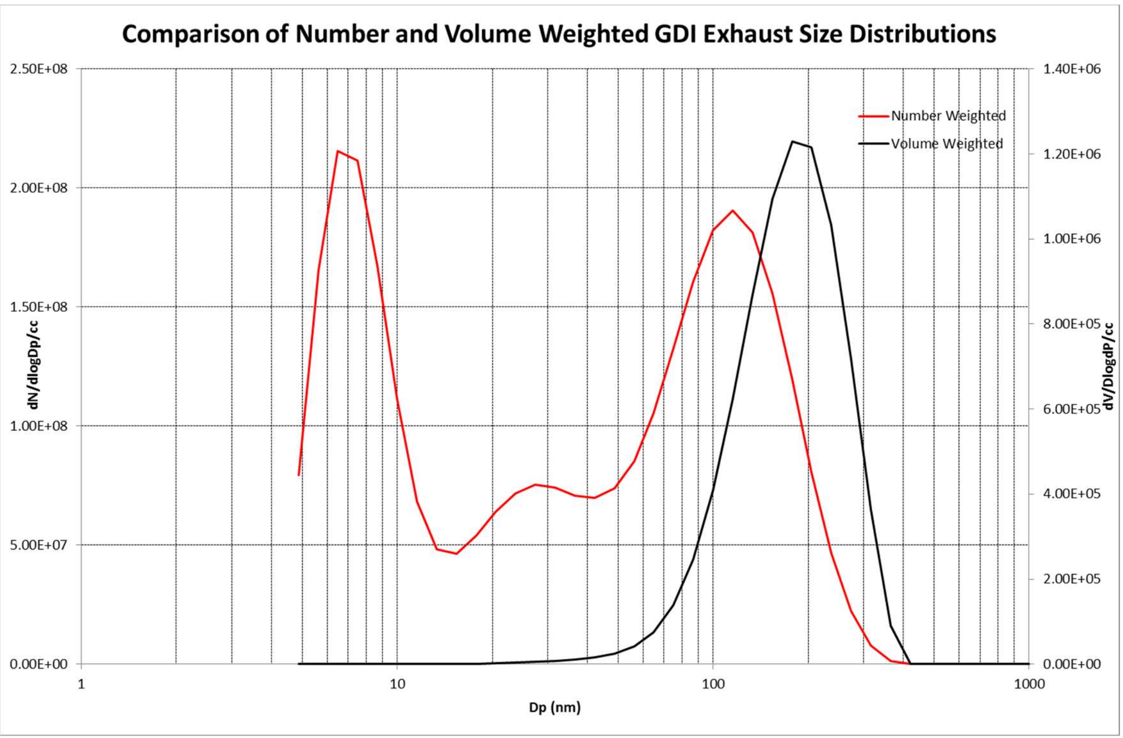


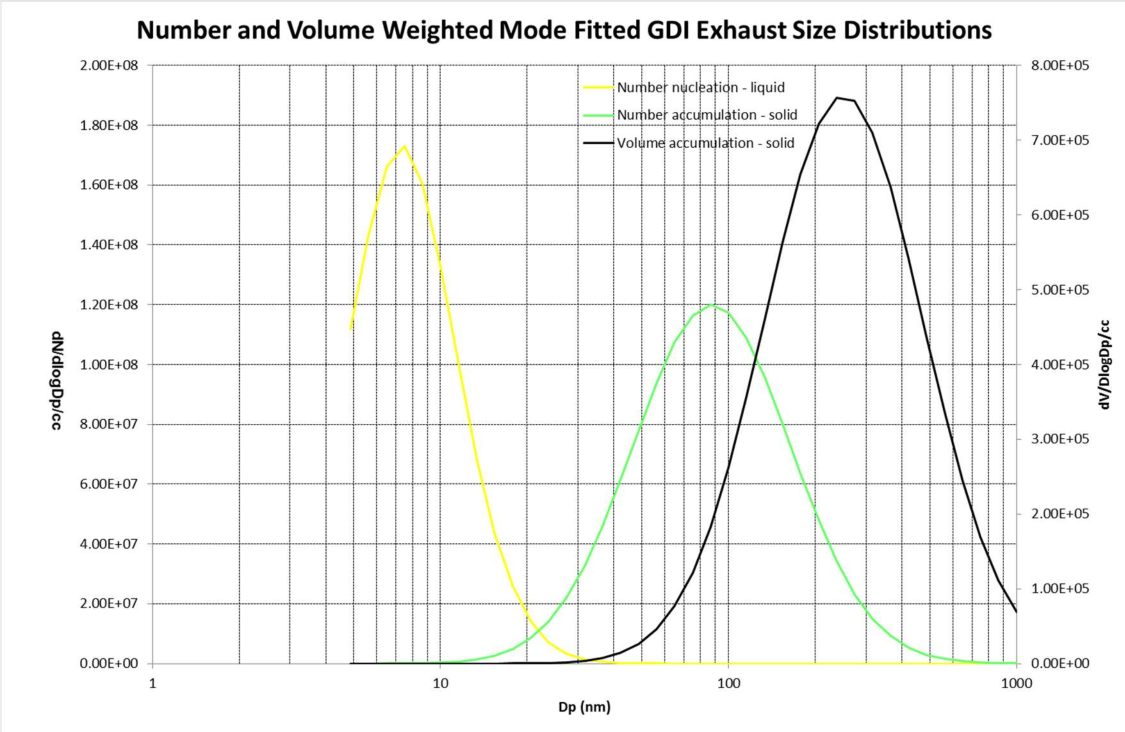
Figure 1: Number and volume weighted size distributions

A nucleation (liquid) mode is present at less than 10nm, and an accumulation (soot) mode at around 120nm Count Median Diameter (CMD). Note that the contribution of the small nucleation particles to the volume (and hence mass) is insignificant.

Since legislation requires only the counting of solid particle number, it is desirable to distinguish between the liquid and solid particles. The DMS500 uses real-time data processing to identify the accumulation (solid) mode and allow it to be handled separately. It also enables the use of a soot calibration to account for the non-spherical nature of soot particles.

It also allows the base instrument noise to be eliminated from the signal. The nature of the DMS500 is such that detector noise will produce a particle signal even when no input is present for the relevant particle size. This is not significant when looking at number weighted size distributions, but when mass weighted size distributions are considered, the mass contained in an noise related 1,000nm particle may be significant compared with the true signal represented by 100nm soot particles from the exhaust.

Mode fitting allows the concentration at size classes which do not have a genuine signal to be set to zero. This allows accurate calculation of particle mass concentration.



Recent additions (2017) to the DMS500 software allow the replication of the 23 nm roll off from the PMP legislation, while retaining future compatibility with other possible measurements (e.g. 10nm).

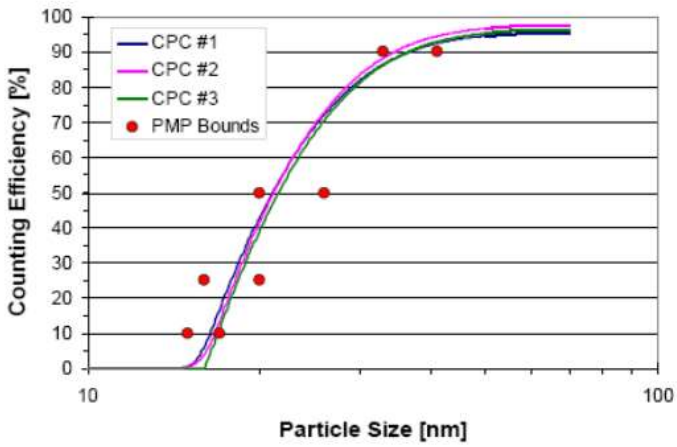


Figure 2 23 nm roll off function of CPC as replicated in software

Practical Mass Measurement with the DMS500

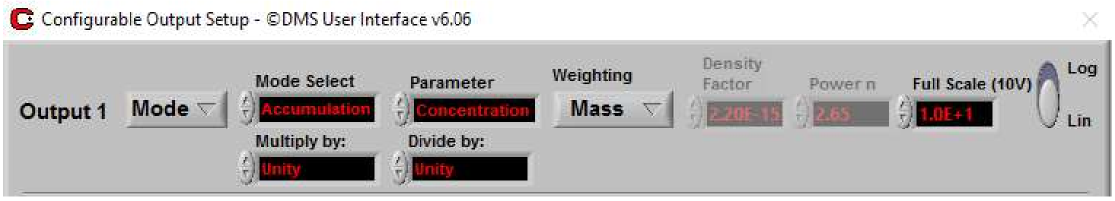
The DMS500 is supplied with an optional calibration file representing the Diesel soot calibration. This allows the user to easily configure the software to provide calculated mass data on Diesel or gasoline exhaust gas. The formula used by the software is shown below, but unless custom settings are required, it can simply be selected, without the need to enter the formula.

$$Mass\ (\mu g) = Density\ Factor\ \times D_p^{Power\ Factor}$$

One of the configurable outputs should be set to select the Accumulation Mode, and then Mass weighting. This will automatically use an appropriate density and power factor. This is encoded into the .dmd calibration file.

For Diesel engine agglomerates, research shows that the DMS500 mass calculation gives good agreement with gravimetric techniques using a density factor of 2.2×10^{-15} and raising the diameter to the power 2.65.

For gasoline engines a density factor of 5.2×10^{-16} and a power factor of 3 are appropriate. The user can also set custom values.



In the example given, configurable output 1 will record the mass concentration in µg/cc. The same value is also sent to Analogue Output 1 as a voltage, in this case 10V corresponds to 10µg/cc or 10,000mg/m^3..

Further real time processing is possible. For example, it is advantageous to calculate not only a mass concentration (µg/cc) but an emission rate (µg/s) or an integrated mass emission (µg). This may be perrformed in two ways, depending on whether raw exhaust is sampled or if the sample is drawn from a CVS tunnel.

If raw exhaust is sampled, then the measured concentration is multiplied on a continous basis by the instantaneous exhaust flow rate. Exhaust flow rate may either be measured directly, or it may be calculated from intake air flow and fuel flow rates.

$$\frac{\mu g}{cc} \times \frac{cc}{s} = \frac{\mu g}{s}$$

Note that the DMS500 references volume measurements to 0°C and 100 kPa and so the exhaust flow rate should be converted to these conditions using Boyle's Law for optimum accuracy.

The DMS500 configurable outputs may be set to perform this calculation in realtime if an external Analogue Input signal for exhaust flow rate is available. Alternatively, the concentration data, either in the recorded file, or output via analogue or AK protocol over Ethernet may be processed to provide emission rate and integrated data.

If sampling in the CVS tunnel, the same equation shown above is used, but is simpler since the tunnel flow rate will remain constant.

Example Data:

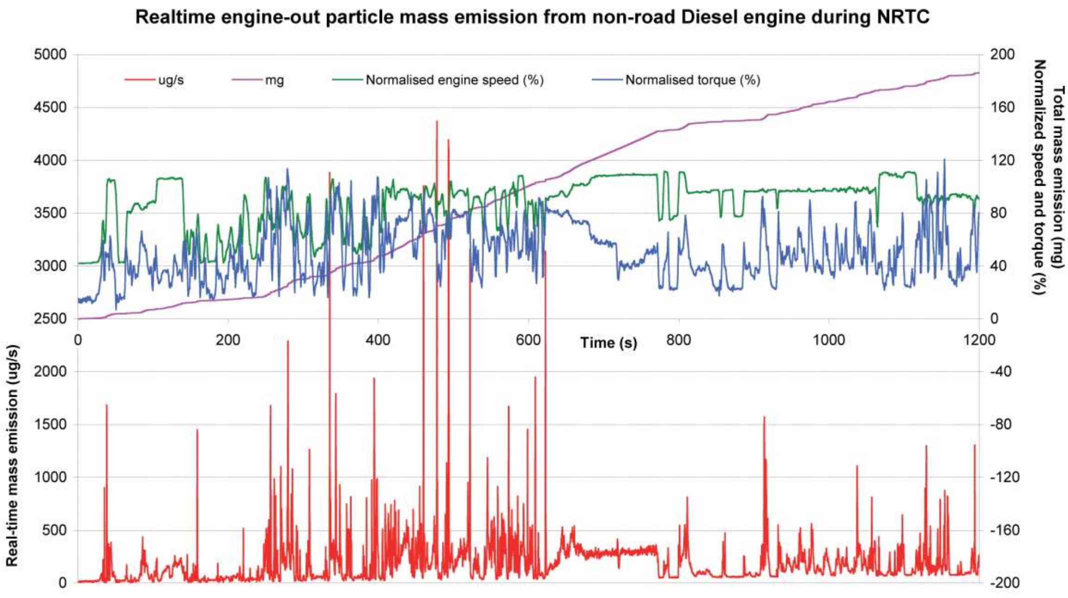


Figure 3: Real-time mass emissions rates and integrated mass from DMS500

Figure 3 shows mass emissions rate (µg/s) and integrated mass emission (mg) from a Diesel engine during the Non Road Transient Test cycle. This cycle has very few points which can be considered steady state, and therefore any measurements of mass concentration must be made on a transient basis.

The DMS500's $T_{10\text{-}90\%}$ response time of 200ms offers a particular advantage in this application, since engine out PM has short duration spikes at high concentration during transient operation, and the spikes are substantial contributors to the total PM.

Conclusions

The DMS500's real-time calculation of mass from both Diesel and gasoline engines offers developers a useful tool for optimisation of calibration of both engine and after-treatment for PM.