Density of particles emitted from a gasoline direct injection engine

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Introduction

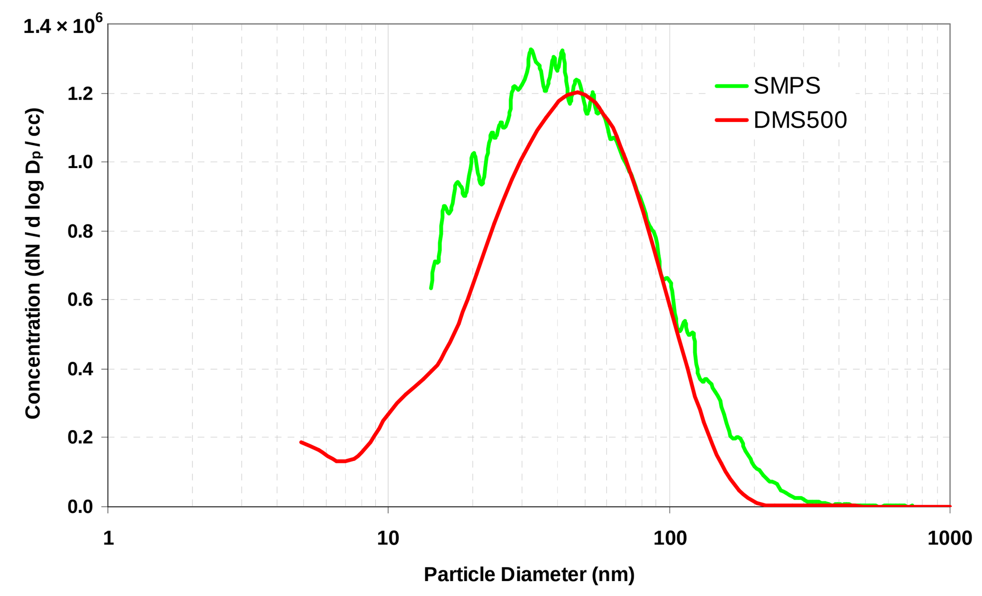
The need to reduce CO_2 emissions is driving automotive constructors to increasingly employ direct injection technology in gasoline engines. Compared to port fuel injection, this enables the use of higher compression ratios, lean unthrottled operation and has synergies with other CO_2 reducing actions such as forced induction and downsizing (Zhao *et al.,* 1999). The engine used here was operated at low speed and light load (1000 rpm, 3.27 bar BMEP). EN228:2004 compliant gasoline was injected in the intake stroke through a multi-hole solenoid injector at a pressure of ~100 bar. The charge was thus nominally homogeneous at ignition.

The Couette CMPA (see panel on right) has previously been used to measured the density of Diesel engine particles (Olfert *et al.*, 2007). In this case the fractal dimension, D_f, such that mass ∝ diameter^{D_f}, was determined to be 2.20–2.48 for regular loads. Previously, an alternative to the CPMA, the Aerosol Particle Mass analyser (APM, see right hand panel) has been used to determine the density of Diesel soot particles (D_f = 2.33–2.41, Park *et al.*, 2003). The ELPI (electrical low pressure impactor) and a DMA have also been previously used to determine the density of particles from a DISI (GDI) engine (Maricq & Xu, 2004), where D_f = 2.30. In the same study the fractal dimension of Diesel soot was found to be 2.35.

Here, aerosol sample was iso-kinetically extracted downstream of a three-way catalyst, then immediately diluted by a factor of 10 with an ejector diluter. Conductive tubing was used for sample transport from the diluter to the CPMA, and the Cambustion DMS500 and TSI SMPS used to obtain particle size spectra.

Spectral Data

During the CPMA measurements, spectra were obtained using a Cambustion DMS500 (Reavell *et al.*, 2002, Symonds *et al.*, 2007) and a TSI SMPS, both sampling downstream of the dilution system. A representative SMPS spectrum was used in the charge correction processing of the CPMA data.



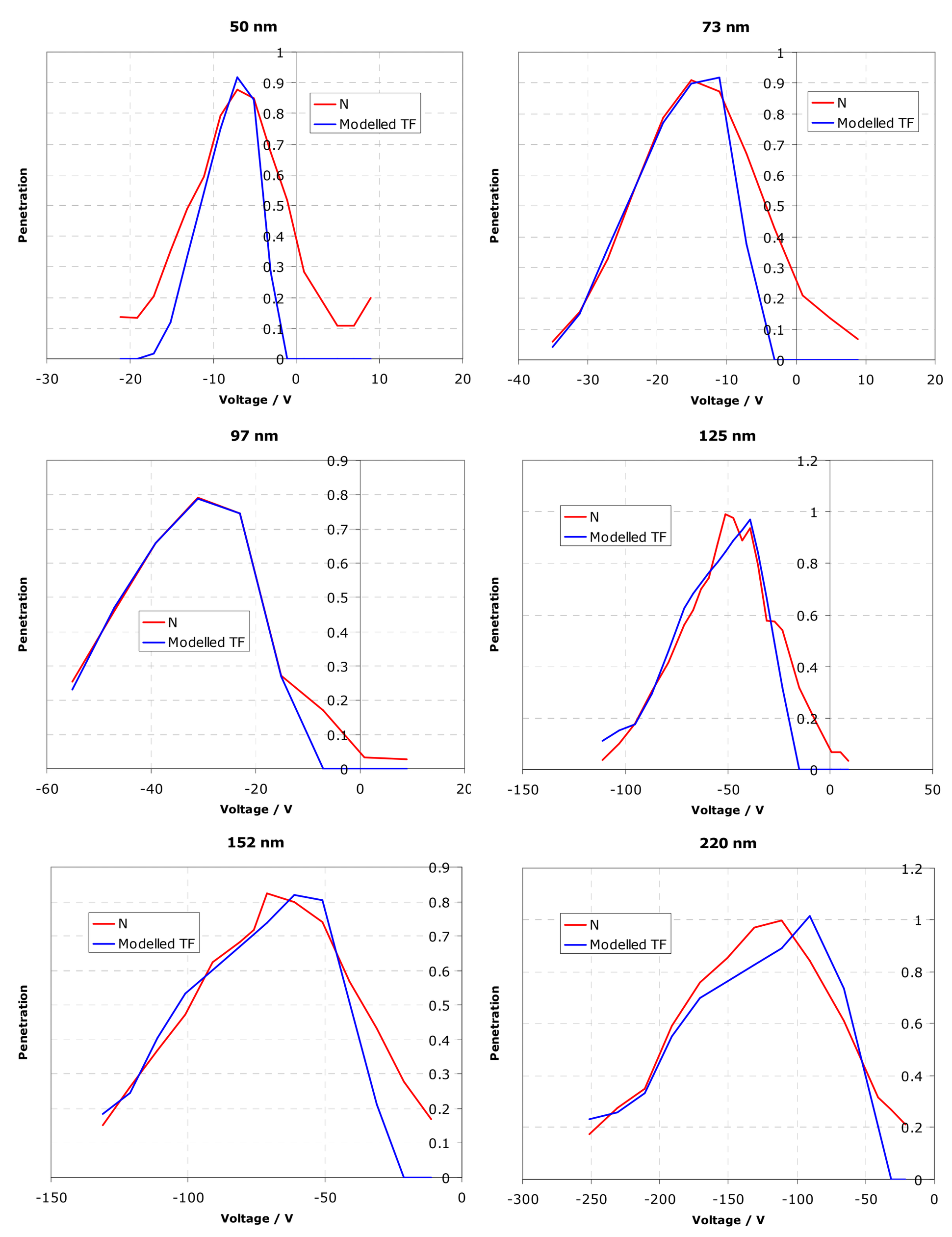
Results

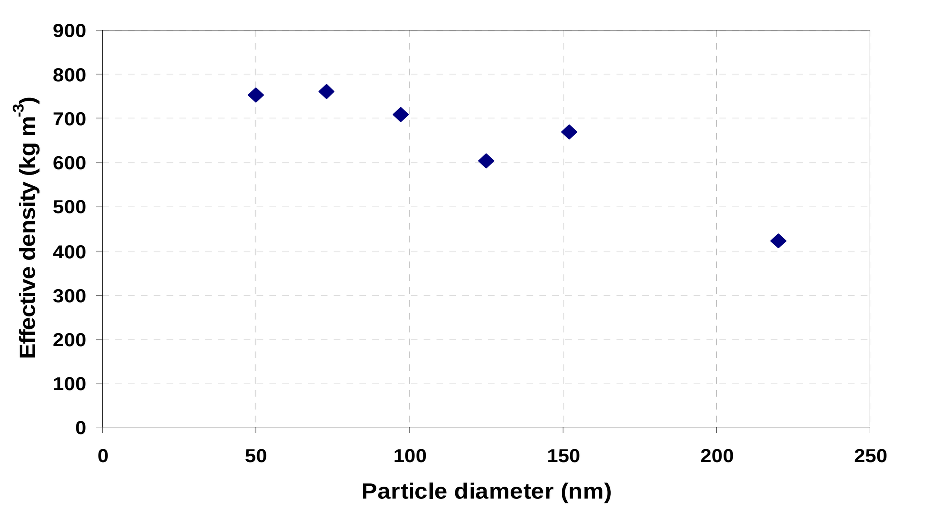
The mass of particles emerging from the CPMA at the maximum penetration voltage, V_c is given by:

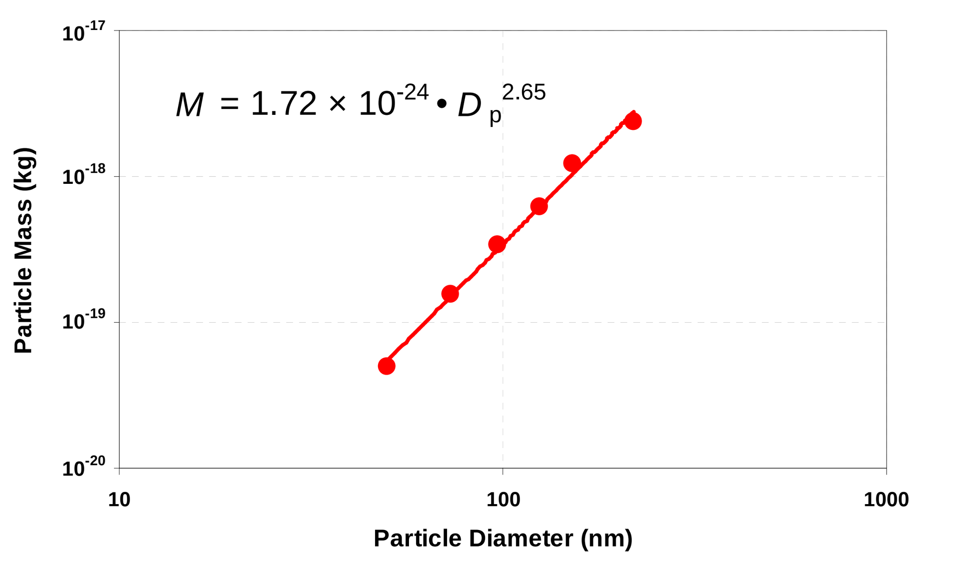
$$m_c = \frac{neV_c}{\omega_c^2 r_c^2 \ln(r_2/r_1)}$$

for mean rotational speed ω_c, cylinder radii r_1, r_2, their mean radius r_c, and n electronic charges. The form of the finite transfer function is given by a simple analytic model of the CPMA (K. Reavell, personal communication). At a given DMA setting, as well as particles with +1 charge at that setting, particles of the same electrical mobility with charges +2, +3… will also emerge at increasing sizes. Their relative populations in the engine aerosol are assessed from an SMPS size spectrum. From these relative populations, and the likelihood of each charge state being achieved from a theoretical model, a weighting is obtained for each possible charge state. These weightings are applied to the theoretical transfer functions for each charge, and then the mass is calculated by optimising the fit of the sum of the calculated transfer functions to the measured transfer function (plots at top right).

The mid-right graph shows the effective density as a function of size, and the bottom right graph shows a power law fit to the measured particle mass at each size. The power law indicates that in this case D_f = 2.65.

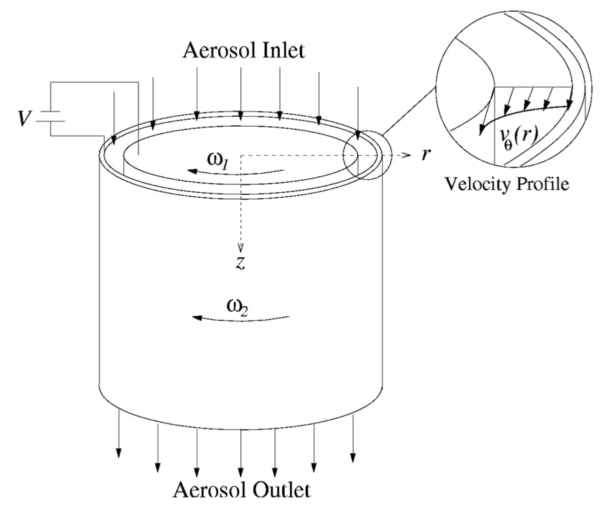


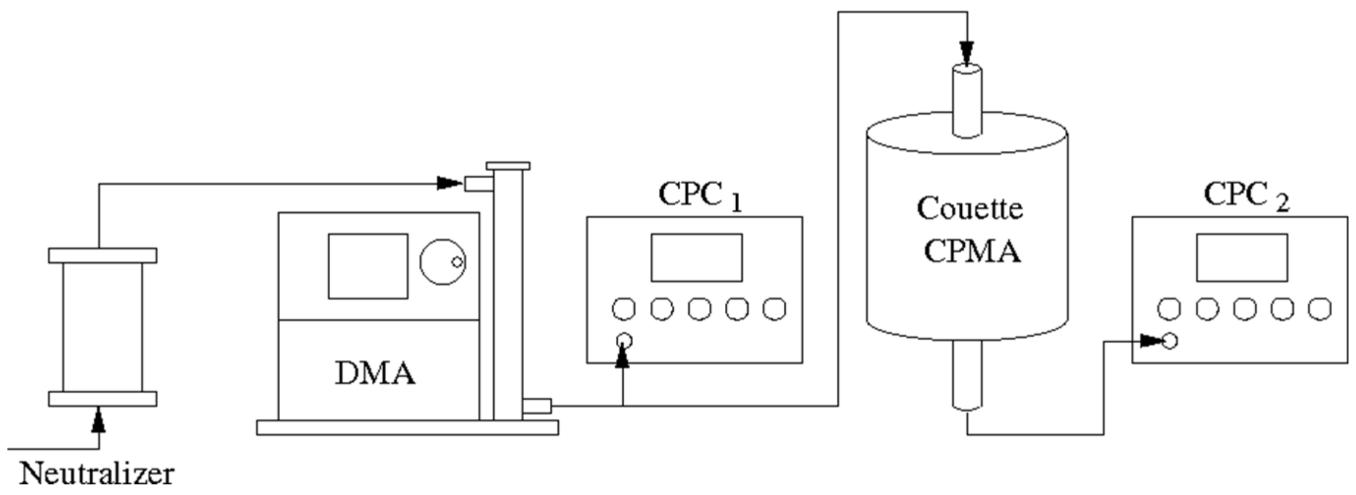




The Couette Centrifugal Particle Mass Analyser

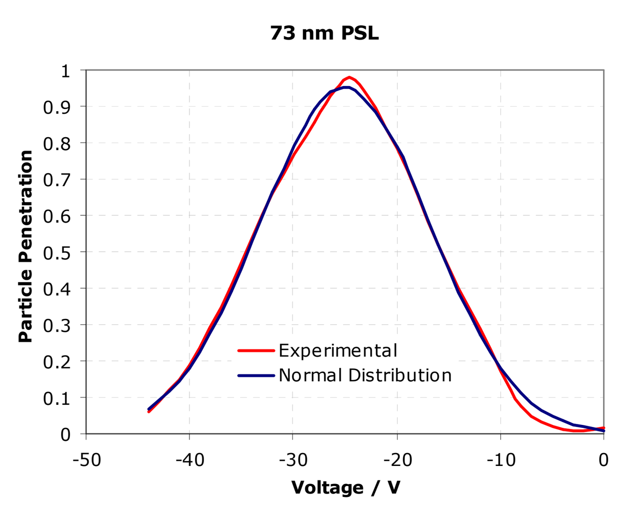
The Couette Centrifugal Particle Mass Analyser (CPMA, Olfert & Collings, 2005) classifies aerosol particles by their charge to mass ratio using opposing centrifugal and electrostatic forces. Compared with the Aerosol Particle Mass analyser (APM, Ehara *et al.*, 1996) the system of forces produced is stable, and hence increases particle throughput. This is achieved by utilising two co-axial cylinders, between which the particles pass axially and the electric field producing potential difference is applied, which co-rotate at slightly different angular speeds (right, diagrams courtesy of Jason Olfert).

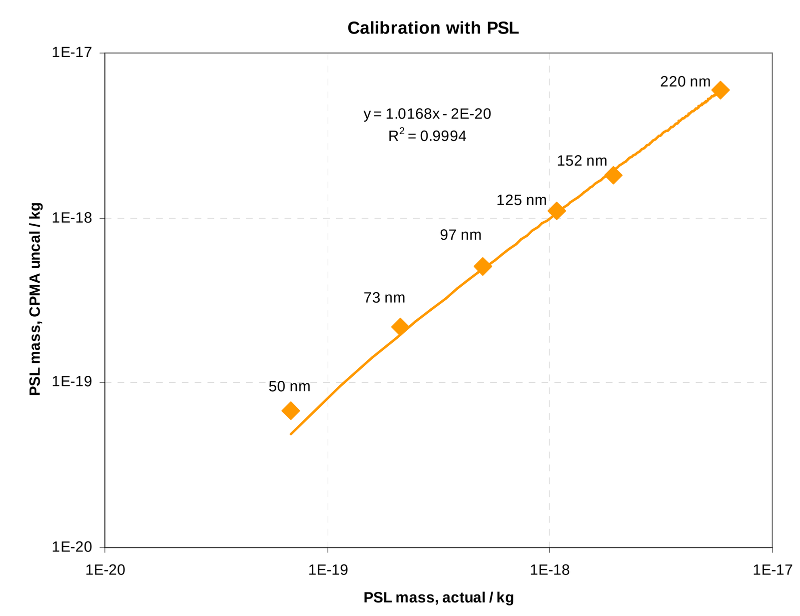




In this study the Couette CPMA is used to measure the dependence of particle mass upon electrical mobility diameter (above). Particles are bipolar charged and then size selected with a TSI 3081 Differential Mobility Analyser (DMA). Post-DMA, the particles will all have at least one electronic charge, and hence will be classifiable with the CPMA. At the selected size, with fixed rotational velocities, the CPMA classification voltage is scanned and the penetration as a function of this voltage is obtained by using two Condensation Particle Counters (CPCs) before and after the CPMA (these may be the same CPC which is switched between the two positions). See the results pane below for details of the data processing used once this transfer function is measured.

CPMA Calibration





The CPMA was calibrated with traceable polystyrene latex (PSL) spheres of known diameter and density. The resultant measured masses at 50, 73, 97, 125, 152 and 220nm were compared with the known values. The source of error was deduced to be a voltage offset and this was compensated for in the engine aerosol measurements.

Discussion

Gasoline engine particulate emissions can vary widely in their size, number density and composition as a function of engine operating conditions. Caution is thus required when interpreting the fractal dimension derived here for GDI aerosol because the data is only available for one engine speed – load condition. Gasoline engine aerosols can have much higher organic to elemental carbon ratios than are generally obtained from conventional diesel engines. The increased fractal dimension cf. diesel engines observed here is possibly related to this difference in volatile particle content. A study of DI gasoline composition (carbon / volatiles) can be found in Price *et al.* (2007), but the engine load therein is very different to this study.

Electrical mobility analysers such as the DMS500 which use a corona discharge to multiply charge particles, when calibrated for standard spherical lab aerosols (e.g. PSL spheres, or with DMA size selected NaCl aerosols) show better agreement with CPC number measurements, or DMA / SMPS size measurements when sampling GDI aerosols than for Diesel. It is necessary to use a different calibration to get the best results for Diesel, due to these particles being more highly fractal, and hence being more highly charged in such instruments' chargers due to increased surface area (Symonds & Reavell, 2007). Satisfactory DMS – gravimetric filter correlations can be obtained with simple spherical particle models (Price *et al.*, 2006) whereas a non-integer D_f is required for satisfactory results with Diesel exhaust (Symonds *et al.* 2007).

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Acknowledgements

We would like to thank Jaguar Cars Ltd for providing the engine used, Dr Jason Olfert, now of Brookhaven National Laboratories, New York, for his advice on the use of the CPMA and kind permission for the reproduction of the diagrams of the system, and Kingsley Reavell for his simple analytic model of the CPMA transfer function.