Density of particles emitted from a gasoline direct injection engine

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Introduction

The need to reduce CO\textsubscript{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\textsubscript{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 plunger injector at a pressure of ~100 bar. The charge was thus nominally homogeneous at ignition.

The Couette Centrifugal Particle Mass Analyser (CPMA, Offert & Collings, 2005) classifies aerosol particles by their mass ratio using opposing centrifugal and electrostatic forces. Compared with the Aerolot Particle Mass analyser (APM, Ehsa, et al., 1999) the system of forces produced is stable, and hence increases particle throughputs. This is achieved by utilising two co-axial cylinders, between which the particles pass axially and the electric field producing particle 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.

The Couette Centrifugal Particle Mass Analyser

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The CPMA was calibrated with tracable 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.

Results

The mass of particles emerging from the CPMA at the maximum penetration voltage, \( V_p \), is given by:

\[
\frac{m}{\lambda} = \frac{e_0 \Omega \lambda^2}{m_e} \frac{1}{\pi^{\frac{1}{2}}} \frac{\ln(\lambda)}{\ln(\lambda)}
\]

for mean rotational speed \( \omega \), cylinder radii \( R \), and mean radius \( \lambda \), and mean electronic charges. The form of the entire 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 \( +2, +3 \ldots \) 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 \( D = 2.65 \).

Spectral Data

During the CPMA measurements, spectra were obtained using a Cambustion DMS500 (Reavell et al., 2006) 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.

CPMA Calibration

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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 of 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 test is correspondingly a very different study to this.

Electrostatic 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 Na\textsubscript{2}CO\textsubscript{3} 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 calibrations can be obtained with simple spherical particles models (Price et al., 2006) whereas a non-integer \( D \) is required for satisfactory results with Diesel exhaust (Symonds et al. 2007).

References


Acknowledgements

We would like to thank Jaguar Cars Ltd for providing the engine used, Dr Jason Offert, 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.

\[ D = 2 \times 10^{-2} + 2.6 \]

\[ \frac{M}{\lambda} = 1.27 \times 10^{17} \lambda^2 \]