Multi-Instrument Characterisation of Particulate Emissions from a Gasoline Direction Injection Engine: Investigation of Size, Volatility and Density

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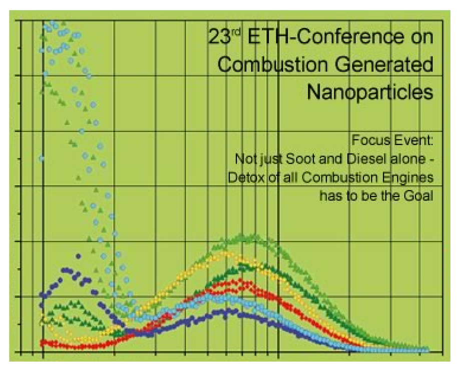

Introduction

Gasoline direct injection (GDI) engines offer higher specific power output and fuel economy compared with port injection gasoline engines, but generally emit more particles (both by mass and number) and are therefore a potential source of ambient particle pollution in urban areas. The introduction of a particle number limit for gasoline vehicles in the Euro 6 emissions standards is expected to lead to widespread adoption of the gasoline particle filter (GPF). Particle emissions from combustion engines are usually a combination of solid particles and condensed semi-volatile material. The solid particles include soot aggregates and ash; the latter can be a source of catalyst poisoning in coated GPFs. In this study, the nature of particulate emissions from a GDI engine was investigated using a range of instruments to determine the size distribution, the effect of removing the semi-volatile fraction and to measure the density.

Method

A 2.0 litre turbocharged GDI engine generating a maximum power of 180kW at 5500rpm was mounted in a transient engine dynamometer cell equipped with a constant volume sampling (CVS) tunnel. The engine was fuelled with Euro 6 Gasoline (E10).

A Differential Mobility Spectrometer (DMS) was used to sample raw exhaust upstream of the turbocharger, with and without a catalytic stripper in the sample line, and with the engine undergoing a Worldwide harmonised Light vehicle Test Cycle (WLTC).

Tests were repeated under steady-state conditions with the engine speed at 2700rpm (where torque at full load was 365Nm). A sample was drawn from the CVS and the number size distribution was measured with a Scanning Mobility Particle Sizer (SMPS) comprising a TSI Differential Mobility Analyser (DMA) 3081 and a Condensation Particle Counter (CPC) 3775.

To investigate the nature of the particulate matter in more detail, DMA-classified particles taken from the peak of each mode that appeared in the size distributions were directed through a solid particle counting system that was set up according to the Particle Measurement Programme (PMP) specification. This included a Volatile Particle Remover (VPR) consisting of an evaporation tube (ET) heated to 300°C, cold dilution and a PMP-compliant TSI CPC 3790 (which has a D50 of 23nm). The diluted flow was also directed to the CPC 3775 (which has a D50 of 4nm). The number mass distributions of the classified particles were then scanned with a Centrifugal Particle Mass Analyser (CPMA).

Raw exhaust sampling during WLTC

Three WLTCs were run on the engine (with cooldown modes in-between), the first without a catalytic stripper in the DMS, then with it connected but not heated ("off"), and lastly with the stripper heated ("on"). As shown in Figure 1a, particle number emissions over the cycle are dominated by an 8nm mode that is largely removed by the catalytic stripper. Figure 1b shows the average number size distributions during the extra high speed section; while semi-volatile 8nm particles were removed, an additional mode at 20nm persisted through the catalytic stripper along with the expected soot accumulation mode at 70nm.

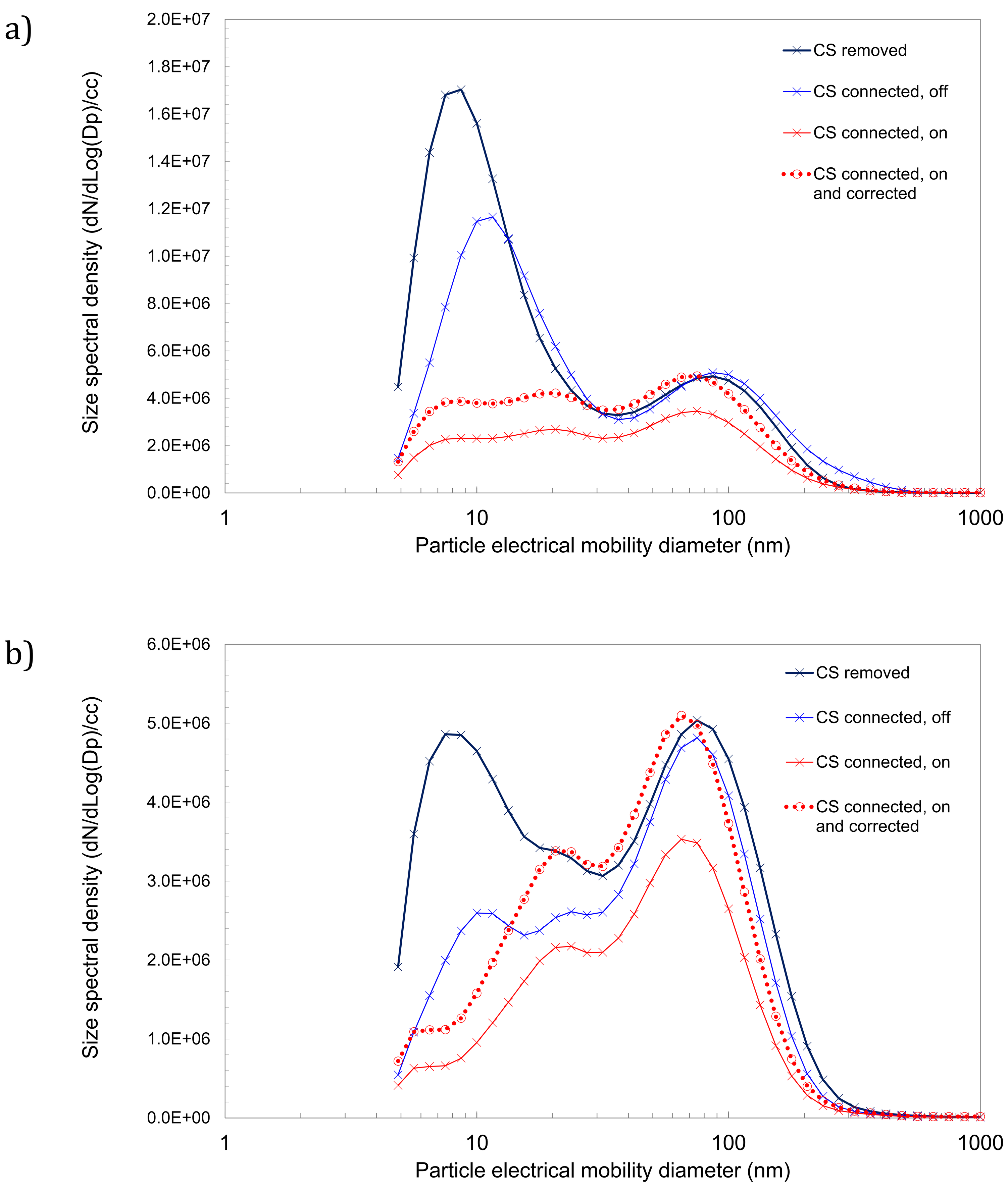

Figure 1: DMS spectra obtained upstream of the turbocharger, with and without a catalytic stripper (CS) in the sample line, a) averaged over the entire cycle and b) averaged over the extra high speed section only.

Dilution tunnel sampling during steady-state operation

While the engine was run at 2700 rpm, diluted exhaust aerosol was sampled from the CVS. In repeated SMPS measurements an apparent shoulder on the main accumulation mode is evident at 20nm (see Figure 2). To verify that these particles are solid, DMA-classified particles were directed through the ET, initially with its heater off and then with the heater activated (see Figure 3).

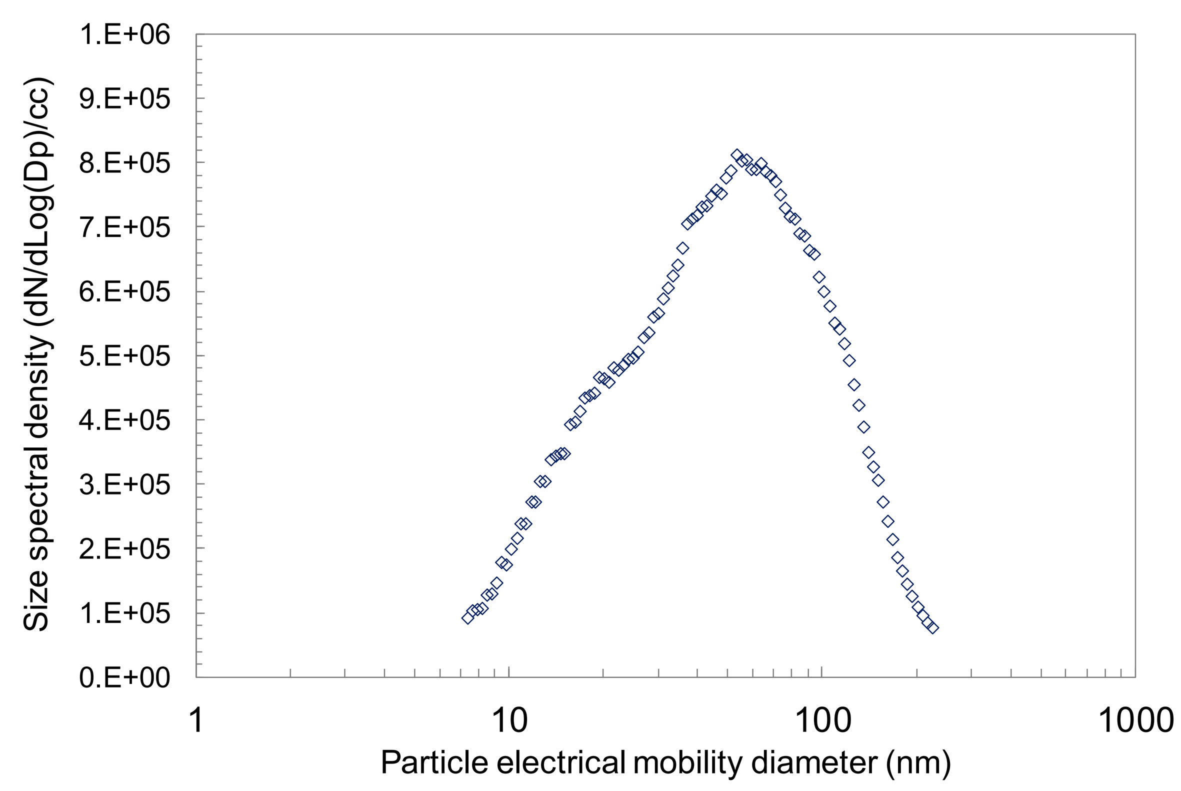

Figure 2: Number size distribution of exhaust particles sampled from the dilution tunnel measured with the SMPS.

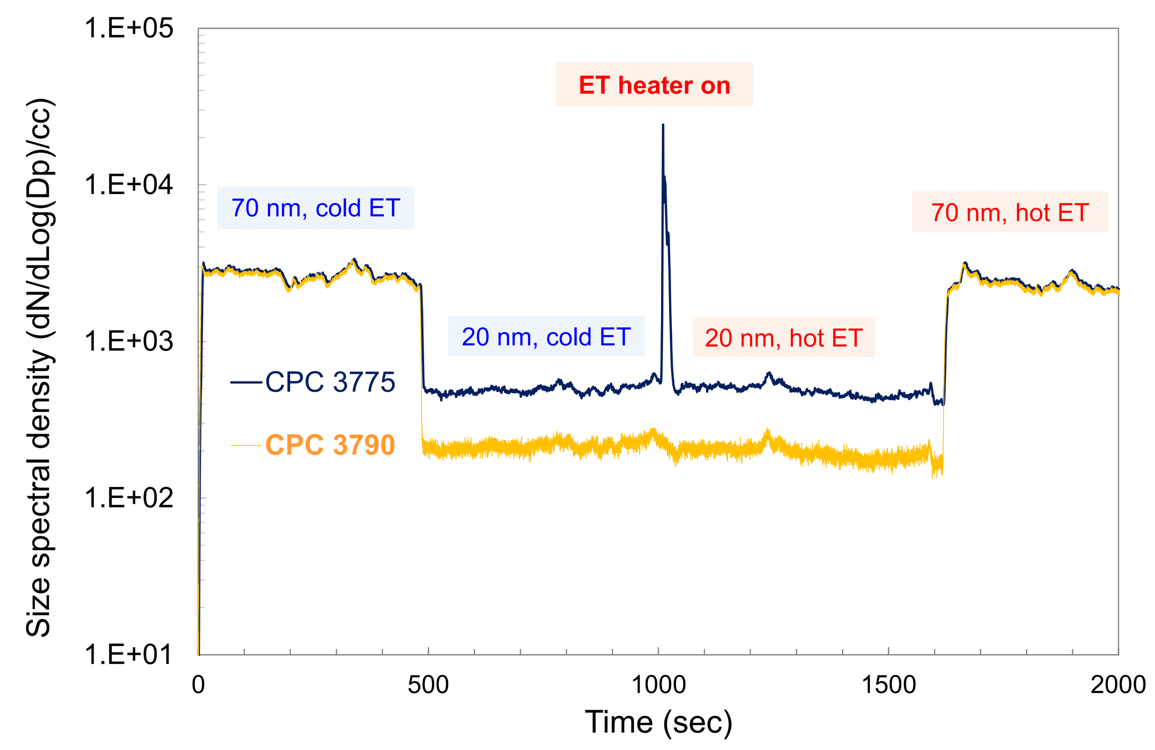

Figure 3: CPC logs while DMA-classified 20nm and 70nm particles are alternately directed through a cold then hot (300°C) ET. The 3775 has a lower cutpoint size (4nm vs 23nm for the 3790) and detects small nucleated particles originating from volatile contaminants within the ET that come off when its heater is activated (reaching setpoint within 30 sec).

The masses of particles selected from the 20nm and 70nm modes with the DMA were scanned with the CPMA; the results shown in Figure 4 are consistent with an effective density relationship for GDI soot aggregates (and are not indicative of some other composition, e.g. metallic ash).

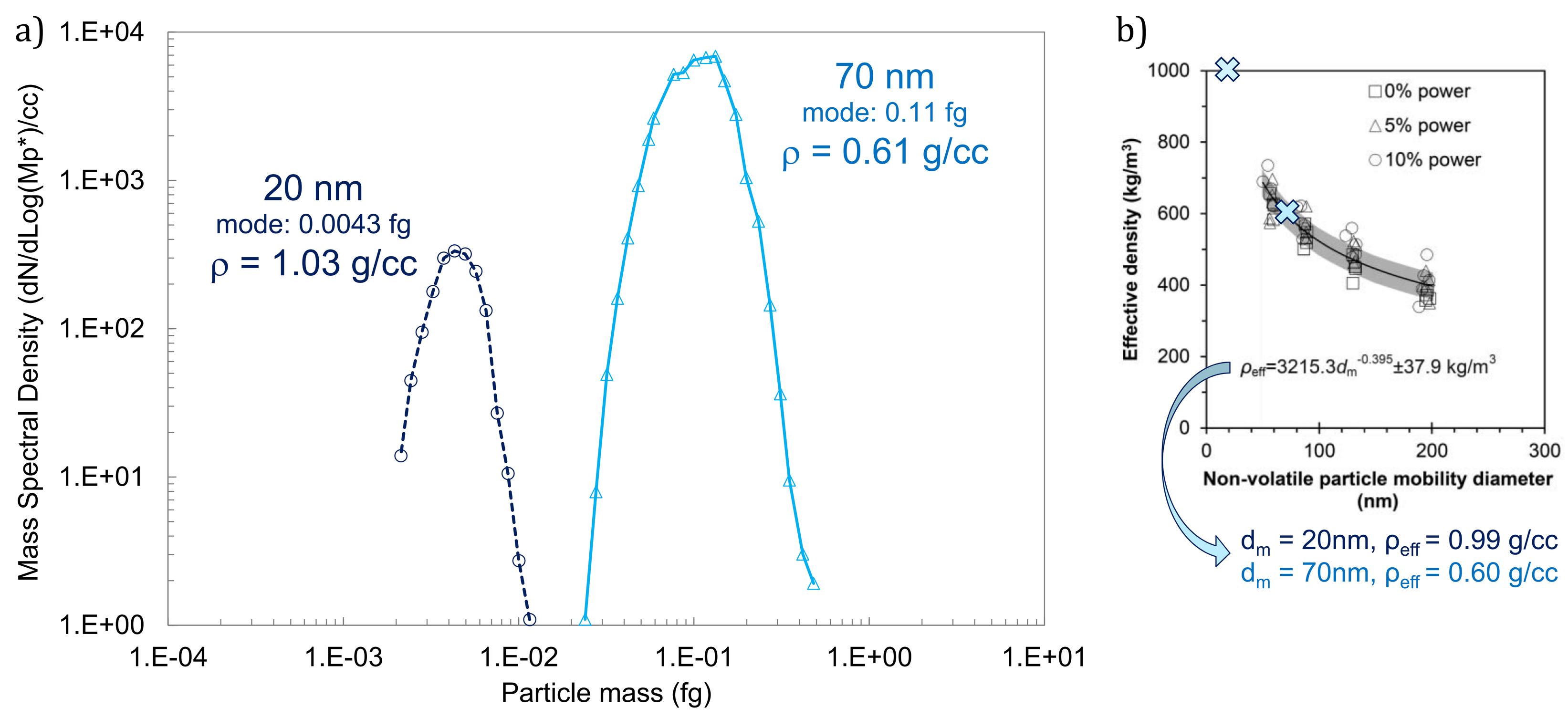

Figure 4: a) CPMA scans of DMA-classified particles taken from the peaks of the modes that appear in the solid particle spectra and b) the effective density values that emerge (blue crosses) plotted with GDI soot data obtained by Momenimovahed & Olfert (2015) who also used the DMA and CPMA in tandem

There are numerous studies in the literature which show that unlike diesel soot, GDI soot size distributions are not lognormal but are instead asymmetric on the log scale with higher concentrations for smaller particles (e.g. Harris & Maricq (2001)) – this is reflected by the data in Figure 2. GDI particles generally exhibit higher mass-mobility exponents than diesel, which indicates a fundamentally different aggregate structure; TEM images in the literature reveal an increase in GDI primary particle size with aggregate size (e.g Barone et. al (2012)).

Further investigation is required to understand the 20nm mode that is distinguished in the raw exhaust DMS measurements and hinted at in the SMPS data from the dilution tunnel.

References

Barone, T.L., Storey, J.M.E., Youngquist, A.D., & Szybist, J.P. (2012). *An Analysis of Direct-Injection Spark-Ignition (DISI) Soot Morphology*. Atmospheric Environment, 268-274

Harris, S. J., and Maricq, M.M. (2001). *Signature Size Distributions for Diesel and Gasoline Engine Exhaust Particulate Matter.* Journal of Aerosol Science, 749-764

Momenimovahed, A., & Olfert, J.S. (2015). *Effective Density and Volatility of Particles Emitted from Gasoline Direct Injection Vehicles and Implications for Particle Mass Measurement.* Aerosol Science and Technology, 1051–1062