

Application of the Pegasor Particle Sensor for the Measurement of Mass and Particle Number Emissions

Leonidas Ntziachristos, Stavros Amanatidis and Zissis Samaras
Aristotle University of Thessaloniki

Kauko Janka and Juha Tikkanen
Pegasor Oy

ABSTRACT

The Pegasor Particle Sensor (PPS) is a small and lightweight sensor that can be used directly in raw exhaust to provide the mass and number concentration of exhaust aerosol. Its operation principle is based on the electrical charging of exhaust aerosol and determination of particle concentration by measuring the charge accumulated on the particles. In this paper we have applied the PPS in a variety of vehicle exhaust configurations to evaluate its performance characteristics. First, the output signal of the instrument was calibrated with diesel exhaust to deliver either the mass or the number concentration of exhaust aerosol. Linear response with the soot mass concentration measured by a Photo Acoustic Soot Sensor and number concentration measured by an Electrical Low Pressure Impactor was established. Based on this calibration, the instrument was then used to measure particle concentrations at levels produced by a gasoline direct injection vehicle and diesel exhaust filtered by particle filters of variable efficiency. Hence, the complete range of concentrations and particle characteristics typically encountered in automotive exhaust has been examined. The results show that the PPS signal can provide a repeatable measurement of aerosol concentration in the exhaust of current vehicles, offering a very good correlation both to the mass and number of particles, as measured by existing techniques.

CITATION: Ntziachristos, L., Amanatidis, S., Samaras, Z., Janka, K. et al., "Application of the Pegasor Particle Sensor for the Measurement of Mass and Particle Number Emissions," *SAE Int. J. Fuels Lubr.* 6(2):2013, doi:10.4271/2013-01-1561.

INTRODUCTION

Diesel Particle Filters (DPFs) have become mandatory in diesel light duty vehicles in Europe and heavy duty vehicles in US and are also expected to be fitted in Euro VI heavy duty vehicles in Europe by 2014. This is the result of their high efficiency in removing exhaust particles, hence significantly reducing the health risks associated with diesel exhaust emissions. In terms of DPF integration to a diesel vehicle, DPFs have to be accompanied by careful engine calibration and management so that the particle loading in the filter remains low and that the frequency of regeneration is reduced to the interest of fuel economy. Moreover, On-Board Diagnostic requirements (OBD) that call for monitoring of the DPF performance have to be fulfilled, in order to warrant the satisfactory operation of DPFs throughout their useful life in real-world conditions.

In Europe in particular, number based emission limits have been introduced for diesel light duty vehicles and accompany the mass-based emission standards [1]. These number limits have been following the recommendations and

sampling protocol requirements that were designed within the Particle Measurement Programme (PMP). The protocol was developed for laboratory testing, primarily for light duty vehicles, and is currently being extended to heavy duty engines as well [2]. Moreover, recent regulatory developments prepare the ground for addressing particle number limits by means of portable emission measurement systems to fulfill in-use compliance testing requirements [3] or even on-board the vehicle to fulfill OBD standards [4].

These requirements for precise engine calibration on one hand, and demonstration that engines and vehicles fulfill the number and mass limits in a variety of testing and operation conditions on the other, bear significant development efforts to the manufacturers. Moreover, they call for particle measurement instrumentation that is precise enough to deliver reliable measurement of exhaust particle mass and number, durable so that it can be used for on-board measurements and economical so that it saves development costs.

Ntziachristos et al. [5] presented a particle measurement sensor (Pegasor Particle Sensor - PPS) with the intention to be used for OBD application. The sensor had the potential, through proper calibration, to be used both for particle mass and number measurement. The capacity of the sensor to sample directly from raw exhaust made it ideal to support OBD monitoring. However, the sensitivity and rapid response time of the sensor showed that it may have characteristics that make it suitable also for use as a normal exhaust particle measurement instrument. Supported by the fact that the sensor required no external dilution for diesel raw exhaust sampling and due to its limited size, the sensor could be used for particle measurements along the tailpipe, including engine-out, pre-DPF and post-DPF conditions.

In this paper we provide a generic calibration of the PPS for both particle mass and number measurements, using typical diesel exhaust aerosol. The sensor calibration is then validated with measurements on a diesel car fitted with DPFs of varying efficiency and a gasoline direct injection (GDI) vehicle. The generic calibration can then be used to approximate particle emissions from other vehicle types and conditions.

EXPERIMENTAL

Pegasor Particle Sensor

The Pegasor Particle Sensor (PPS) is based on the electrical detection of aerosol following the “escaping current” technique, which was first described by Lehtimäki [6]. A sample of the exhaust gas is charged by a corona-ionized flow as it is being pumped by an ejector diluter built in the sensor's construction. While the majority of the corona ions return to the grounded sensor's body due to their high electrical mobility, a small quantity is lost with the charged particles exiting the sensor. This “escaping current” is a measurement of the particle concentration in the exhaust gas.

The sensor responds to particle size with a function that lies between the response to particle number and mass [5]. Therefore, use of the sensor to measure either of these properties requires calibration. Ideally, calibration has to be conducted with the aerosol the sensor will be exposed to in actual measurements. However, since vehicle exhaust aerosol does not substantially differ from recent technology vehicles [7], use of a generic calibration may already provide adequate information for a wide range of vehicle technologies.

Mass and Number Calibration

Instrumentation and experimental layout

The sensor was calibrated at the Laboratory of Applied Thermodynamics for mass and number particle concentration measurement using aerosol produced by a Toyota 1ND-TV 1.4L Euro 5 compliant light duty diesel engine (Table 1). In actual vehicle installations, this engine is used in combination with exhaust aftertreatment, including a diesel particle filter.

We have utilized no aftertreatment in our case but direct engine-out emissions as an aerosol source for calibration.

A schematic of the experimental setup is shown in Figure 1. The PPS was installed in the tailpipe of the engine, some 2 m downstream of the exhaust manifold, directly sampling raw exhaust. The probe inlet and short transfer line of the sensor were maintained at 200°C by means of a wall heater to avoid condensation and thermophoretic losses. The body of the sensor was maintained at 250°C by means of an external heater again to avoid condensation and thermophoresis. The exhaust aerosol was therefore always maintained at a temperature above 200°C with this sampling setup. Hence, limited condensation should occur, which means that the PPS signal corresponds to the soot concentration of the exhaust gas. In all tests presented herein, the PPS operated with its trap voltage set at 400 V. This value was selected as the optimum setting in order to achieve efficient collection of the free ions and avoiding the collection of charged particles.

Table 1. Engine and fuel characteristics.

Displacement	1364 cm ³
Bore x Stroke	73 mm × 81.5 mm
Max. Power	88.7 hp (66.2 kW) at 3800 RPM
Max. Torque	190 Nm from 1800 to 3000 RPM
Compression Ratio	17.9:1
Combustion System	Direct Injection
Intake System	Variable geometry turbocharger with intercooler
Valve Mechanism	SOHC, 2 valves per cylinder
Fuel Injection System	Common Rail (1600 bar), 6 hole injectors
Camshaft Drive	Timing Chain
Exhaust Gas Treatment:	EGR, equipped with cooler and catalyst
Emission standard	Euro 5
Fuel	Commercial diesel according to EN590:2009 (max sulfur 10 ppm wt, 7% vol. max biodiesel)

The signal of the PPS was compared to the measurement of an AVL Micro Soot Sensor (MSS), which was the instrument of choice to measure soot concentration in the exhaust gas. The MSS is based on the photo-acoustic principle. Modulated light produced by an infrared laser source is absorbed by the airborne soot sample. This is thermally expanded thus creating acoustic waves which are detected by a microphone. Through calibration, the instrument can deliver the soot mass concentration. The MSS was installed in the tailpipe, in proximity to the PPS, by means of a pressure and temperature reduction probe.

Particle number concentration was measured by means of a Dekati Electrical Low Pressure Impactor (ELPI) and a Scanning Mobility Particle Sizer (SMPS). The SMPS consisted of a TSI 3080 Electrostatic Classifier with a TSI 3081 Long-DMA connected to a TSI ultrafine CPC 3776.

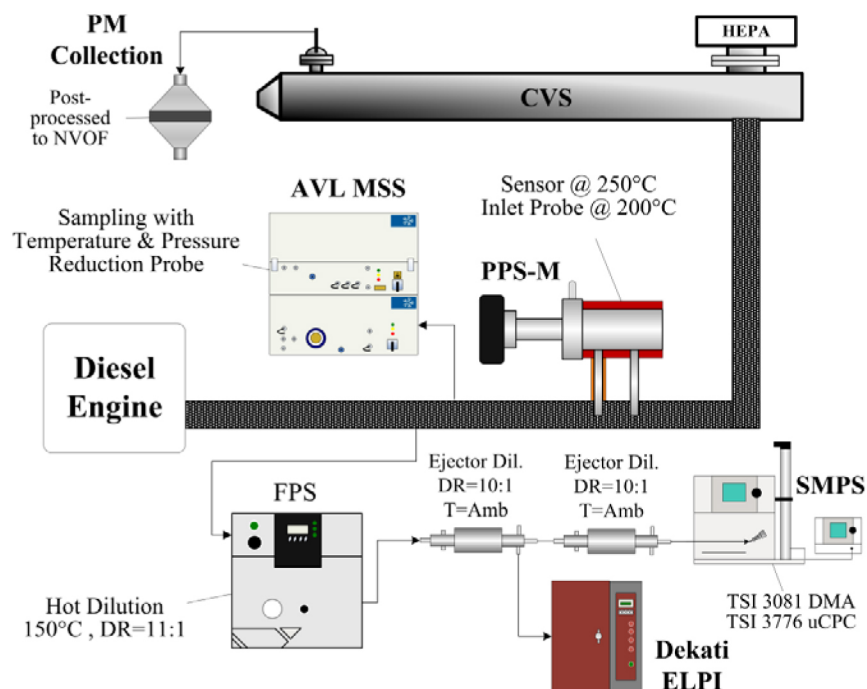


Figure 1. Experimental setup used for the mass and number calibration of the sensor.

The ELPI was used as the prime instrument for particle number measurement because it follows a similar principle to the PPS for particle detection (unipolar particle charging). The SMPS was used to correct the ELPI signal, as will be shown in the next section. Both instruments sampled aerosol through a Dekati Fine Particle Sampler (FPS) operating at 150°C with 11:1 dilution ratio, in series with two Dekati ejector diluters operating at ambient temperature and 10:1 nominal dilution ratio. The ELPI was sampling from the first ejector diluter while the SMPS was sampling from the second one. It was decided for those measurements not to use any thermal treatment for the aerosol upstream of the ELPI and the SMPS. Preliminary tests showed that the high soot concentration at engine out conditions did not lead to formation of measurable quantities of externally mixed volatile particles. Therefore, for reasons of simplicity and in order to reduce particle losses, no thermal treatment has been used.

The tailpipe was also connected to a Constant Volume Sampling (CVS) tunnel where the exhaust gas was primarily diluted and conditioned. A flowrate of 600 m³/h (calculated at normal conditions) was maintained in the CVS tunnel by a positive displacement pump. Particulate Matter (PM) mass was collected on 47 mm PTFE-coated fiber filters (Pallflex TX40H120-WW). After the measurement, the filters were post-processed to determine the Non-Volatile Fraction (NVOF) mass, as an additional reference for the soot concentration emitted. The removal of the volatile organic fraction was achieved by heating the PM filters in a step-wise fashion, up to 200°C for 2.5 h in an N₂-atmosphere.

Calibration measurement protocol

The diesel engine was set to six different speed/load combinations in order to achieve a wide range of soot and particle number concentrations. The selected engine points are shown in Table 2. The engine was left to stabilize for a sufficient time at each change of state, which was at least 15 min prior the measurement. The exhaust gas temperature in the tailpipe at the sampling location was also monitored.

Table 2. Engine points selected for the mass and number calibration.

Engine Point	Engine Speed [rpm]	Engine Load [Nm]
1	1500	20
2	1500	25
3	2000	70
4	2000	40
5	2500	40
6	2500	50

This protocol was repeated for three different sample flowrates of the sensor ranging between 2.1-5.4 liters per minute (lpm), in order to explore the impact of the flowrate to the signal of the sensor. These flowrates were realized by installing flowrate reduction orifices at the inlet of the sensor. The flowrate achieved in each condition was measured with a TSI 4143 flowmeter which refers to standard conditions defined at 21.1°C and 101.3 kPa.

Calibration parameters

The conversion of the PPS signal to particle concentration was based on the introduction of “L” and “N” coefficients for mass and number respectively, as shown in Table 3. The calibration coefficients are supposed to provide the number and mass concentration of exhaust aerosol, when directly multiplied to the signal of the PPS sensor. The determination of the numerical values of the two parameters is explained in the Results section of this study.

Table 3. Calibration Parameters.

	Mass [mg/m ³]	Number [cm ⁻³]
Signal	PPS [fA]	PPS [fA]
Coefficient	L [mg/(m ³ × fA)]	N [1/(cm ³ × fA)]
Calculation	Mass = L × PPS	Number = N × PPS

Validation of Calibration

In order to check the validity of the calibration provided, the sensor was used in transient and steady state tests with two different vehicles, including a gasoline direct injection one. The next sections describe the experimental conditions during these tests.

Vehicles and instrumentation

The PPS was installed in the tailpipe of a diesel Euro 4 compliant Honda Accord 2.2 i-CTDi and a stoichiometric gasoline direct injection spark ignition (DISI) Euro 5 compliant 1.4l VW Golf TSI (Table 4). The diesel vehicle in its original configuration was equipped with an oxidation pre-catalyst and a two-stage oxidation underfloor catalyst. In this study the diesel vehicle was tested in alternative configurations to simulate various exhaust emission levels, by replacing the underfloor catalyst with four DPFs, which included a fully functional one and three artificially compromised ones (Table 5).

Particle mass was determined using an AVL Micro Soot Sensor, that was directly connected to the tailpipe of each vehicle. Moreover, the exhaust was connected to the CVS and the solid particle number concentration above 23 nm was determined by a CPC 3010D following the PMP testing protocol [8]. An ELPI was also connected directly to the CVS in order to monitor the aerodynamic particle size distribution in real time.

The fully functional DPF (normal DPF) was a SiC non-catalytic one (5.66×6 in, 300 cpsi, 2.5l, 12 mm substrate thickness). Compromised DPFs #1, 2 and 3 were of the same type as the normal one but approximately 10%, 15% and 25% respectively of their inlet channel plugs were removed.

Table 4. Specifications of vehicles used for the validation of the calibration.

	Honda Accord i-CTDi	VW Golf TSI
Fuel	Diesel	Gasoline
Displacement [cc]	2204	1390
Fuel Injection System	Common Rail	Direct Injection Spark Ignition
Max Power [kW/rpm]	103/4000	90/5000
Max Torque [Nm/rpm]	340/2000	200/1500
Aspiration	Turbocharged	Turbocharged Stoichiometric
Cylinders	4	4
Certification	Euro 4	Euro 5
Year	2006	2012
Mileage [km]	~80000	350

Table 5. Vehicle exhaust gas aftertreatment configurations.

Vehicle	Configuration	Exhaust gas aftertreatment
Honda Accord i-CTDi	Normal DPF	EGR, Pre-oxidation catalyst, DPF
Honda Accord i-CTDi	Compromised DPFs # 1, 2 & 3	EGR, Pre-oxidation catalyst, partially damaged DPFs (~70-90% Efficiency)
VW Golf TSI	Default	3-Way Catalyst

Vehicle measurement protocol

The diesel vehicle measurement protocol consisted of both transient and steady speed tests. In particular, the diesel vehicle was tested over the New European Driving Cycle (NEDC) which is the legislated cycle for the type approval of light duty vehicles in Europe. This driving cycle was conducted for both “cold” and “hot” engine start conditions. Additionally, three alternative driving cycles were included in the test procedure; the so-called Artemis Urban and Road driving cycles, which are considered to be more representative of the real-world urban and rural driving conditions and the Worldwide harmonized Light-duty Test Cycle (WLTC) which is currently under development (version 5) as a replacement to the NEDC for certification of Euro 6 light duty vehicles. Due to measurement constraints, WLTC was executed as a hot-start cycle. The speed profile vs. time of each cycle is presented in Figure 2. In addition, tests at constant cruising speeds of 50 and 120 kph were conducted in order to study the PPS performance at steady-