1.10.2018

White Paper PPS-M

Background - Particle size is not well defined

Fine and nanoparticles can be defined in many ways. Especially when defining the particle size and concentration. Particle size can be measured either off-line or on-line. Off line techniques typically give out particle filter mass concentration. Off-line techniques are seldom used to define particle size. When this is done, electron microscopy is typically used to measure particle geometric size. When measuring particle concentration with off-line techniques, several artefacts enter into play. When particles, especially from engine exhaust are collected on a filter, the filter media itself reacts with the exhaust gas particle thus having an effect on the final result.

On-line techniques measure particles in several different ways and extract different metrics out of the particles depending on the technique used. When measuring particle size and concentration simultaneously, most commonly used detection methods are optical or electrical (electrical mobility, aerodynamic particle size). In electrical detection the extracted data is converted into size and concentration information using known conversion formulas. Formulas enable the user to extract one or more of the following quantities; particle size distribution, total particle mass, total particle surface area or total particle number concentration.

It is very important to know what metrics are measured and that those seldom match with each other 100%.

Pegasor Particle Sensor PPS-M

Technical Description

The Pegasor Particle Sensor (PPS) is based on the electrical detection of aerosol following the “escaping current” technique, which was first described by Lehtimäki [1]. 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 and concentration with a function that lies between the response to particle number and mass [2, 4].

Pegasor particle sensor has been calibrated to both total particle mass and total particle number concentration by Laboratory of Applied Thermodynamics in Thessaloniki, Greece (LAT) [3].

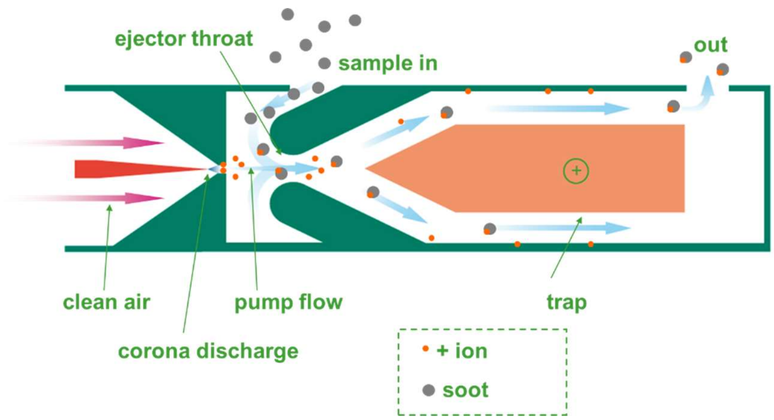

Fig. 1. *Pegasor particle sensor schematics*

Fig. 2. *Pegasor particle sensor PPS-M*

Pegasor particle sensor features the world's fastest fine and nanoparticle measurement technique giving out simultaneously total ultrafine particle mass and total particle number concentration in real time from 10 nm and up. Additionally PPS-M is a non-collective, flow through device which enables it to work continuously without maintenance for extended periods of time. PPS-M is designed to measure raw engine exhaust without dilution. PPS-M has no consumables. The most important features and benefits are given below.

Features

- Real time measurement. Fastest fine particle measurement device in the world. 0,2 s response time
- Total particle mass and total particle number measurement simultaneously from 10 nm and up
- Lightweight and compact size. Length 40 cm, weight 3,3 kg
- Sensor can be heated up to 200 °C. Sensor sampling lines (minimum length 1 m, 2-3 meters recommended) condition the sensor ingoing sample to 200 °C at the sensor inlet. Extracted sample temperature at the sampling point can be from temperatures as low as -40 °C up to 850 °C.
- Raw undiluted hot measurement possible
- Flow through design
- Very low maintenance need

Benefits

PPS-M has no consumables. Periodic cleaning of the insulators is enough when sensor is used according to instructions. Annual calibration at manufacturer's site is provided for some customers Q&A purposes.
PPS-M has extensive self-diagnostics to ensure correct measurement results at all times. Sensor informs the user when cleaning of the sensor is necessary (10 x before the contamination has any effect on the result). Additionally, all critical parameters (corona current, corona voltage and trap voltage) can be recorded on the data file with alarm function attached, if out of set range.

Specifications

- Sensor temperature self-regulated to 200 °C.
- Self-regulated (to 200 °C) 2-3 m sampling line recommended for ease of use. 1 m minimum. Extracted sample temperature can be from -40 °C up to 850 °C. For high temperatures section of uninsulated sampling tube must be used to cool the sample to 200 °C before entering the sensor sampling line so that it does not create any melting of the flexible conductive heated sampling line. Sample temperature will be 200 °C when entering the sensor
- No dilution needed
- Time response 0,2 s (measured)
- Measured ultrafine particle size range adjustable from 10 nm and up
- Trap voltage adjustable from PPS-M Plotter software. Trap voltage determines the lower cut size of the sensor (10 nm, 23 nm or other)
- Concentration range for particle number 300 $1/cm^3$ up to $1*10^9$ $1/cm^3$
- Concentration range for particle mass 1 $\mu g/m^3$ up to 300 mg/m^3 (size distribution dependent)
- Sample pressure –20 kPa - +100 kPa relative to ambient
- With inlet sampling restriction plate maximum concentration range can be increased
- Weight 3,3 kg
- Clean air/Nitrogen supply 10 LPM @ 0,15 MPa
- Data acquisition GUI (laptop, PPS Plotter software), programmable analog out (4 channel DAC). CAN Bus and AK Protocol interface (optional)

- Operating voltage 24 V
- Continuously self-diagnosed for sensor loading (+several other parameters)

PPS-M Strengths

PPS-M has been designed for affordable aerosol concentration measurement from variable locations; e.g. indoor-air, outdoor-air, engine exhaust and stack emissions. Competing devices are typically labor consuming and require frequent service and plenty of consumables/user attention.

PPS-M has no cross sensitivity to compounds such as NO_x or O_2. PPS-M is measuring aerosol, which is a particle suspended in gas, whether in solid or liquid phase or the combination of both. Instrument cross sensitivity can sometimes make data analysis difficult. E.g. gravimetric filter can react with the exhaust gas. Some other instruments are known to be cross sensitive to e.g. NO_x and O_2. PPS-M is measuring well defined aerosol concentration with no interference nor material dependence in the aerosol itself. In fig 3. the measured parameters of three most common engine particle mass exhaust measurement devices are shown.

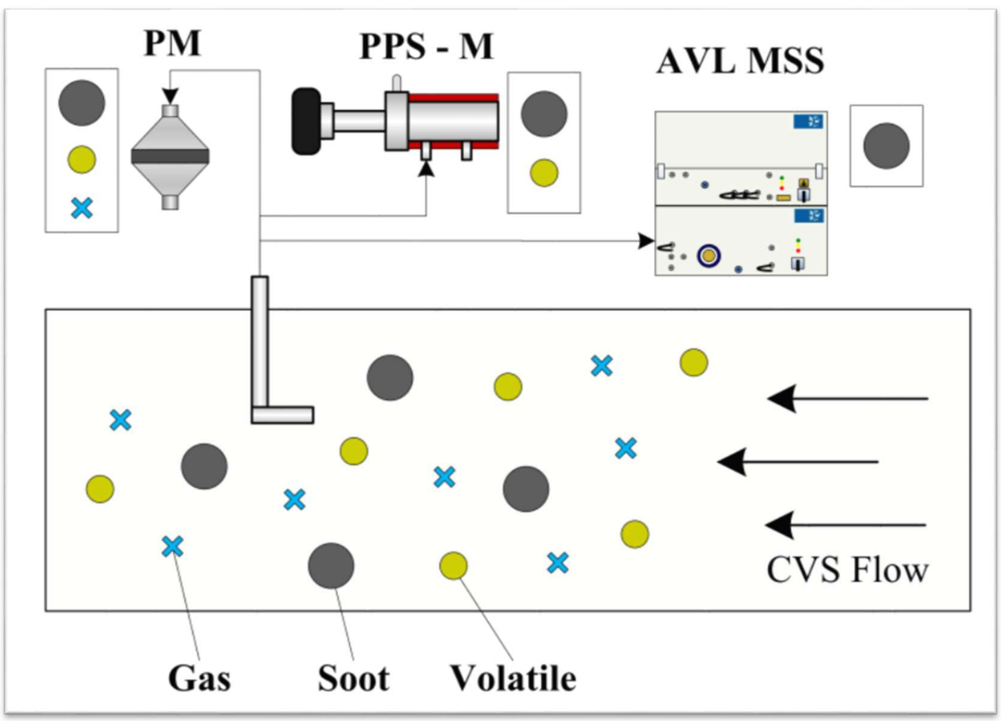

Fig. 3. *An example of what different particle mass measurement devices measure. PPS-M measurement is well defined since it measures aerosol.*

PPS-M requires no sample conditioning. In sample conditioning hot exhaust gas is cooled to room temperature by diluting the sample with cool air. Preventing formation of new particle modes such as nucleation mode or heterogeneous condensation of semivolatiles on existing particle surfaces is difficult. And particle size is often altered. This is considerable cost saving for PPS-M operation. No extra sampling system is needed and no sampling artefacts exist. An example of PPS-M installation is shown in fig. 4.

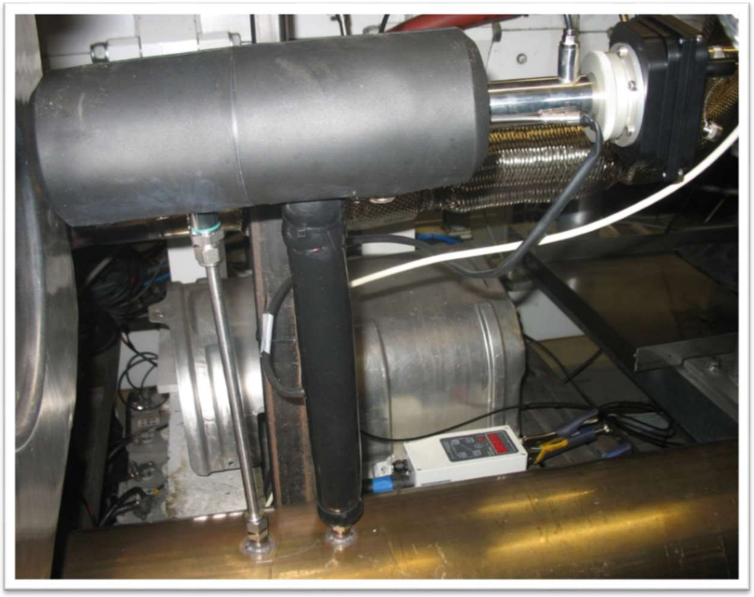

Fig. 4. *Pegasor particle sensor PPS-M installed to measure raw hot exhaust. Sampling line and the sensor is heated to 200 °C. Sensor is insulated and sample is extracted using 45 ° sampling probes facing downstream the exhaust flow. 1m sampling line is enough to condition any sample from -20 °C to 850 °C to 200 °C at the sensor inlet. For sample extraction from temperatures higher than 200 °C, uninsulated stainless steel tube is needed to cool the sample to 200 °C at the sampling line inlet. 2-3 m sampling lines are recommended for ease of use. Especially when measuring on board vehicle.*

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. 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 Fig 5. 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.

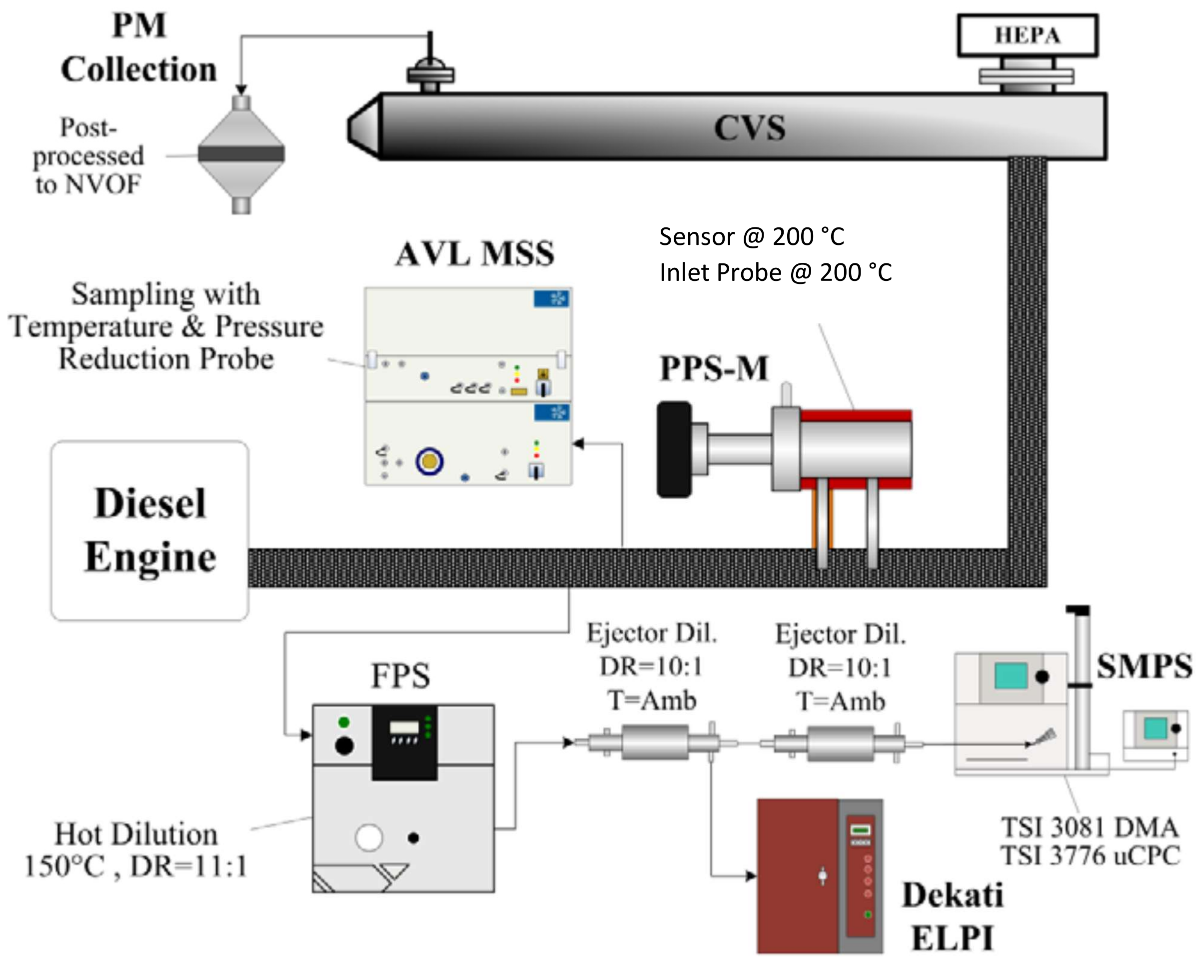

Figure 5. *Experimental setup used for the mass and number calibration of the sensor [3].*

The conversion of the PPS signal to particle concentration was based on the introduction of "L" and "N" coefficients for mass and number respectively. 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. Calibration Parameters are shown in Table 1 below.

Table 1. *Calibration Parameters [3]*

	Mass [mg/m^3]	**Number [cm^{-3}]**
Signal	PPS [fA]	PPS [fA]
Coefficient	L [$mg/(m^3 \times fA)$]	N [$1/(cm^3 \times fA)$]
Calculation	Mass = L × PPS	Number = N × PPS

Based on the measurement results, the generic calibration coefficients for converting the signal of the sensor to mass and number concentration can be expressed as a function of the sample flowrate by the equations below

$$L\left(\frac{mg}{m^3 fA}\right) = \frac{6.3\times10^{-5}}{Q_{in}(stdlpm)}$$

$$N\left(\frac{1}{cm^3 fA}\right) = \frac{288}{Q_{in}(stdlpm)}$$

The flowrate (Q_{in}) is expressed in std lpm (21,.1 °C, 101.3 kPa) and should be determined at the heated (200 °C) sample line inlet and the sensor at its normal operation temperature (200°C) [3].

Adjustable Trap Voltage to Set Lower Particle Cut Size from 10 nm and Up

PPS-M has an internal trap electrode which can be operated at different voltages thus adjusting the sensor lower cut particle diameter. E.g. 60 V corresponds to 10 nm lower cut and 400 V corresponds to 23 nm lower cut. Trap voltage can be adjusted by PPS Plotter software to anywhere between 0 V up to 2000 V. A graph showing the cut diameter as a function of trap voltage is shown in fig. 6.

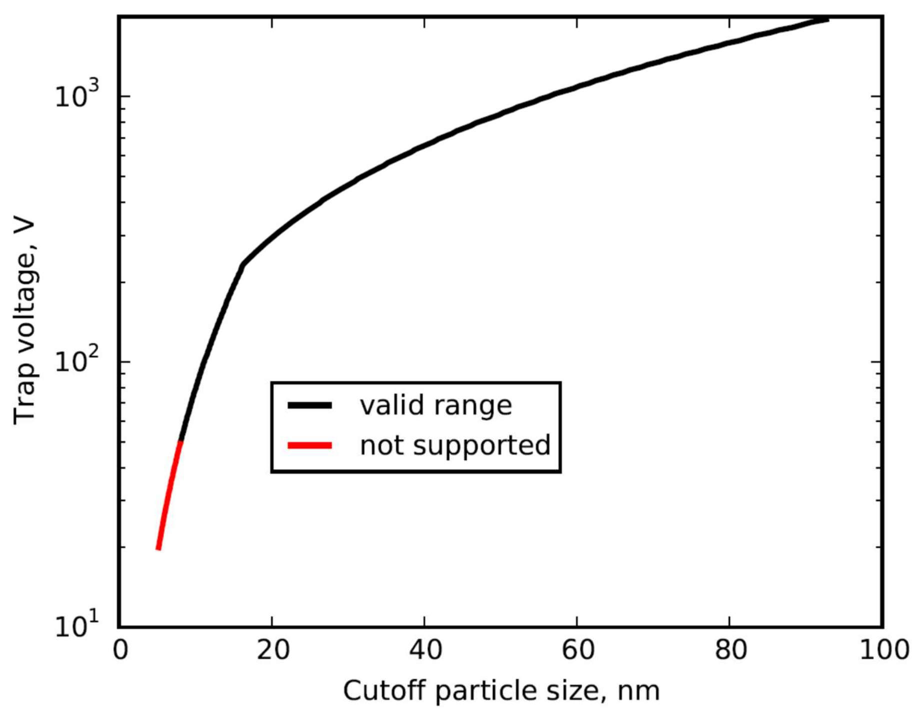

Figure 6. *Cutoff particle size as a function of Trap voltage.*

Measurement Data

PPS-M has been compared to several instruments in the market that measure particle mass and particle number concentration. All instruments are measuring different quantities of the particle concentration. Even though both MSS and CPC are fairly slow instruments averaging data over several seconds, agreement with PPS-M is good with both instruments.

PPS-M is recording sharp peaks as they are (0.2 s time response t_0-t_{95}) thus making data analysis easier and more exact. User can freely change engine parameters during the measurement and no attention is needed to PPS-M. Sensitivity and concentration range are so big that no sensor adjustment is needed. Fast response of PPS-M is clearly seen in fig. 7. PPS-M can detect even the fastest transient emissions giving insight to engine and aftertreatment development and optimization.

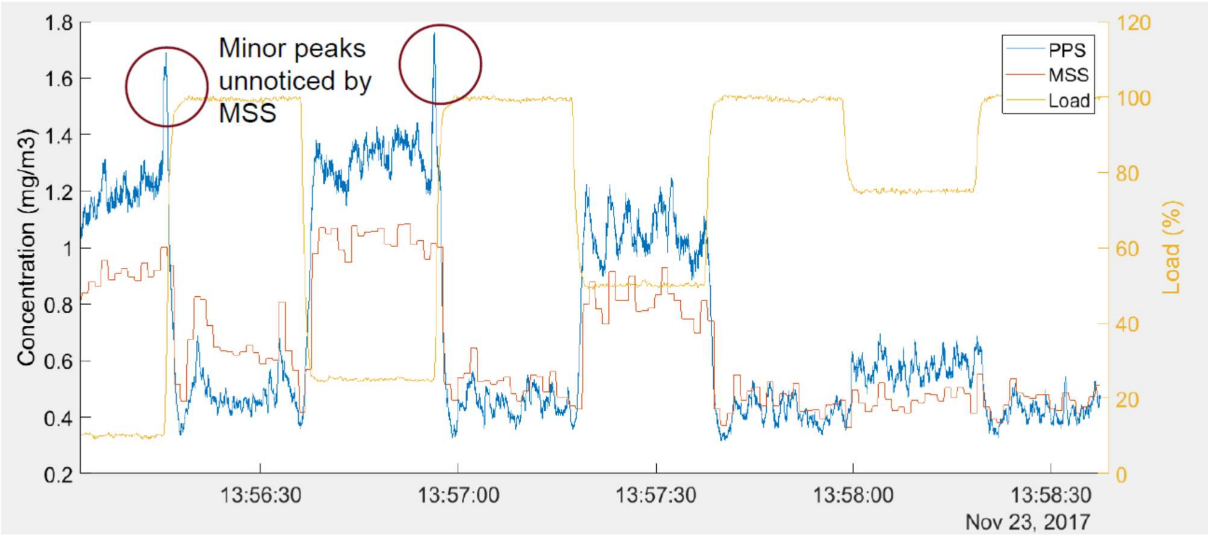

Figure 7. 2000 RPM. *Diesel engine testing showing fast response of PPS-M in case of engine parameter change. Sharp and fast peaks in raw exhaust go unnoticed by slow, integrating instruments. Also, there is significant time delay. Data courtesy of AGCO Power.*

Fast response of PPS-M reveals details from exhaust particle concentration not seen by any other instrument. Examples of such details are shown in fig.8. and 9.

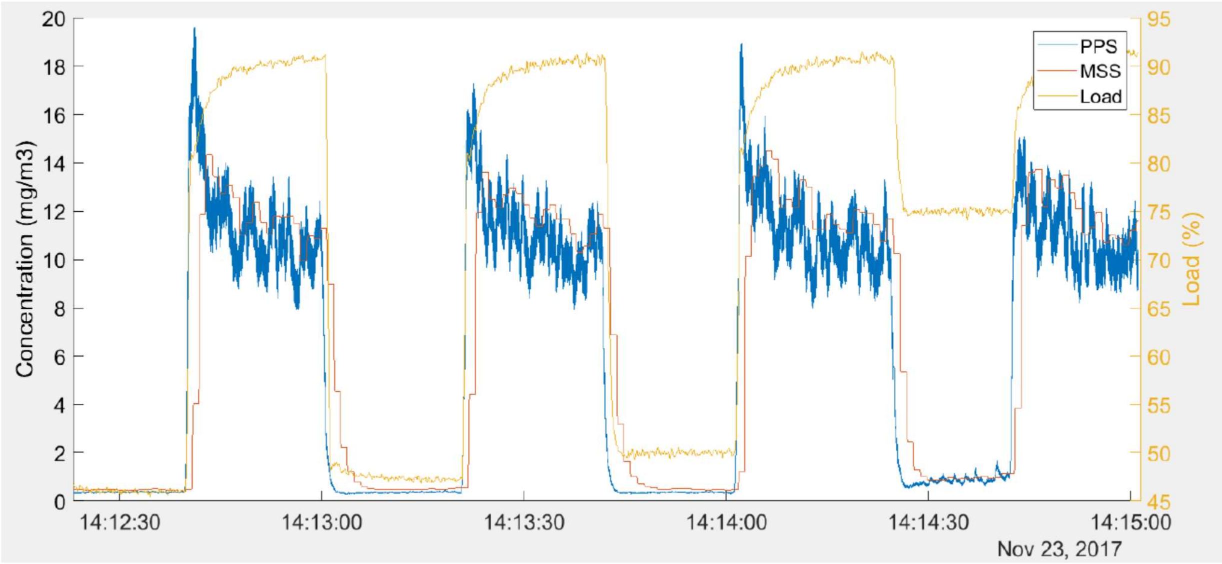

Figure 8. *At low engine speed (800 RPM) the engine particle emissions fluctuate as seen from PPS-M data. This fluctuation is real, but reasons behind are yet unknown/not studied. Please note the fast response time of PPS-M, which enables more detailed and exact analysis of the reasons behind fluctuations. Data courtesy of AGCO Power.*

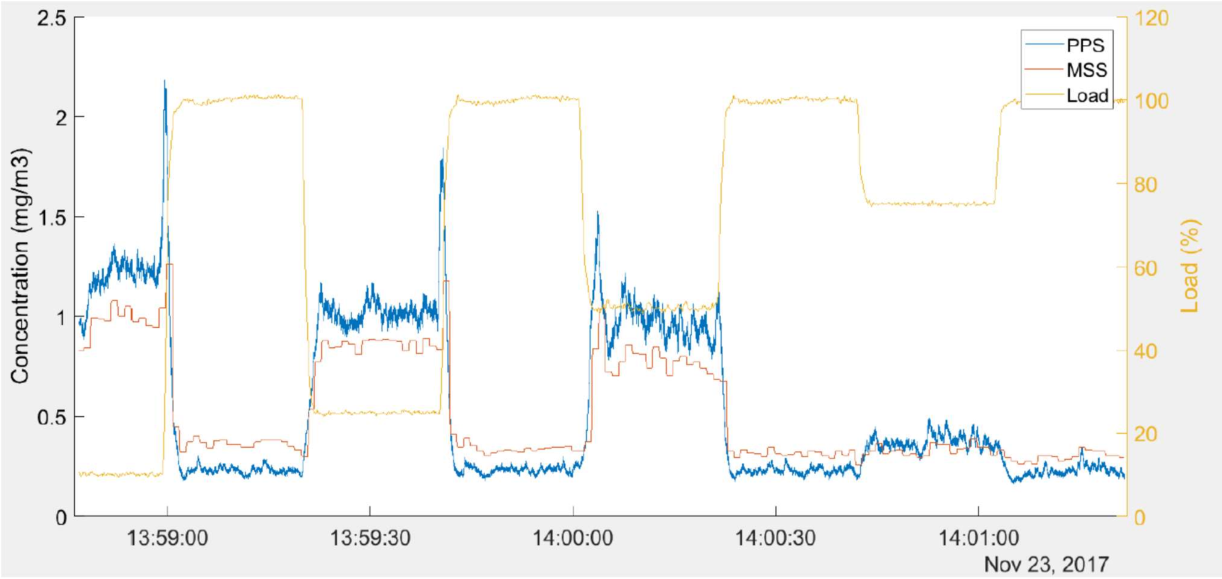

Fig. 9. *At higher speed 1800 RPM the ripple in particle emissions is not existent. Again, there are some deviations between PPS-M and AVL MSS. Data courtesy of AGCO Power.*

PPS-M has also been compared in several cases to CPC's. Again PPS-M is a very fast device and data averaging is needed to make the instrument response functions to match in transient tests. Fig. 10. shows comparison data between PPS-M and CPC in steady state.

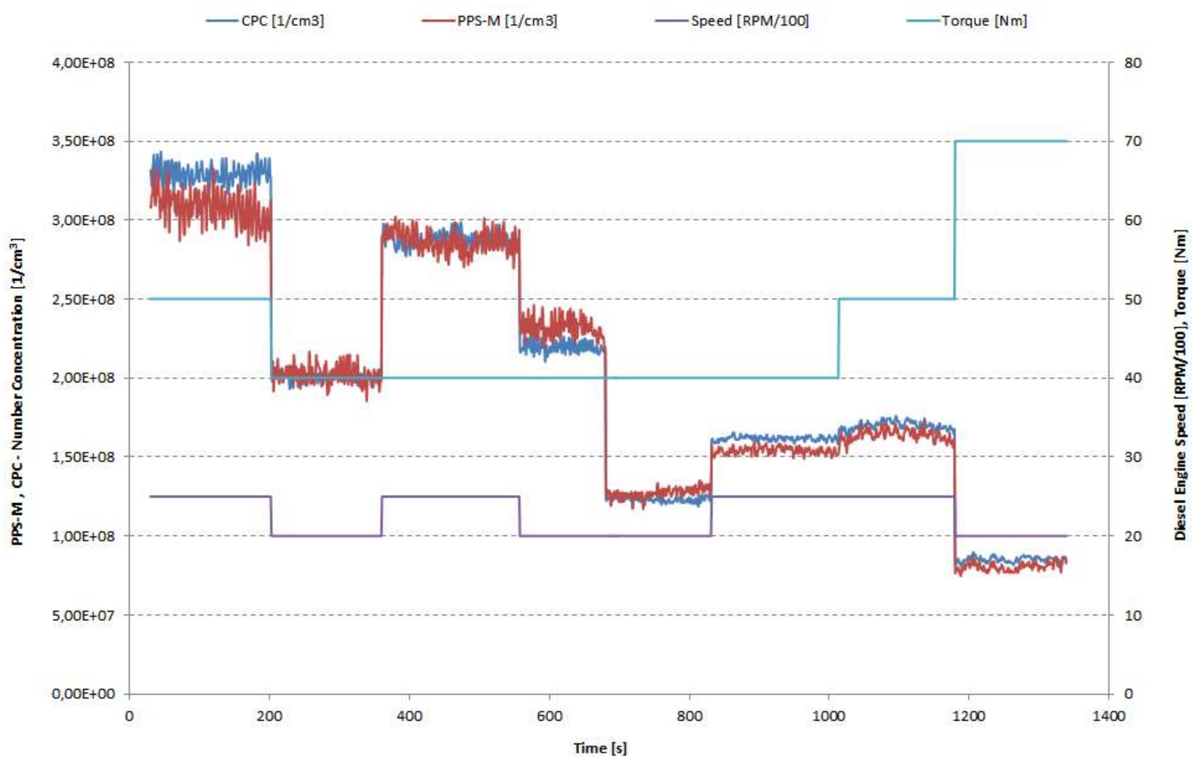

Figure 10. *Comparison between PPS-M and CPC in steady state. Data courtesy of LAT***.**

Summary

PPS-M offers world's fastest fine and ultrafine particle concentration measurement. PPS-M measures ultrafine particle number concentration and mass concentration simultaneously from 10 nanometers and up.

PPS-M operates up to 200 °C thus eliminating negative effects of semivolatiles such as nucleation mode. Sampling line is self-regulated to 200 °C. PPS-M does not require any sample conditioning such as dilution. 200°C sampling line, minimum 1 m and maximum 8 meters in length conditions any sample from -40 °C to 850 °C. In very hot sampling uninsulated tube must be used at the sampling point to cool the sample to to 200 °C before entering the heated flexible sampling inlet line so that no damage is caused to the conductive tube media.

PPS-M includes PPS Plotter graphical user interface to set up the sensor operation parameters, monitor and record data. Several other data communication possibilities are also available (CAN Bus, AK Protocol, analog output etc.) for easy integration into existing data collection infrastructure. PPS-M is self-diagnosed and it informs the user on any action needed to keep the sensor data reliable and accurate.

Scientific Publications

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- M. Besch et al., (2011), 'Assessment of novel in-line particulate matter sensor with respect to OBD and emissions control applications', Proceedings of the ASME 2011 Internal Combustion Engine Division Fall Technical Conference, ICEF2011 October 2-5, 2011, Morgantown, West Virginia, USA, ICEF2011-60142.
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- Ruzal-Mendelevich, Michal, David Katoshevski, and Eran Sher. “Controlling nanoparticles emission with particle-grouping exhaust-pipe”. In: Fuel 166 (2016), pp. 116–123.

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- Marc Besch et al., (2011), ‘In-Use NTE PM Measurement Methodology using an In-Line, Real-Time Exhaust PM Emissions Sensor’, 15th ETH Conference on Combustion Generated Nanoparticles, June 26-29, 2011, Zürich, Switzerland.
- F. Gensdarmes et al., (2011), ‘Evaluation of Pegasor PPS Response Time for Real Time Aerosol Concentration Measurements’, EAC 2011, September 4-9, 2011, Manchester, UK.
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- M. Besch et al., (2012), ‘On-Road Particle Matter Emissions Assessment from a Compliant HD Diesel Truck While Driving Across the US’, 22nd CRC Real World Emissions Workshop, March 25-28, 2012, San Diego, USA.
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[3]. L. Ntziachristos et al., (2013), 'Application of the Pegasor Particle Sensor for the Measurement of Mass and Particle Number Emissions', SAE Int. J. Fuels Lubr. 6(2):521-531, 2013, doi:10.4271/2013-01-1561.

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Notes