Portable Emission Measurement Systems (PEMS) for Heavy Duty Diesel Vehicles PM Measurements: the SEMTECH Portable Particulate Measuring Device (PPMD) and the EU PEMS Program Experience

Lauretta Rubino, Oliver Franken
Sensors Europe GmbH, Feldheider Str. 60, 40699 Erkrath, Germany

Portable Emissions Measurement Systems (PEMS) represent a robust and accurate solution to study the in-use emissions of combustion engines. The application of PEMS is ranging from large heavy duty engines to light-duty vehicles and more recently to off-road mobile machineries. While PEMS instrumentation and the test methods are mature for gaseous emissions, the development of portable PM instruments and their test protocols remain a challenge, as simultaneous progress take place in the engine and after-treatment technology [1,2].
The European Union is following the same route as the Unites States by checking the in-use behaviour of heavy-duty diesel vehicles for both gaseous and PM emissions.
PEMS instruments are currently under evaluation within the EU PM PEMS program to check their feasibility to measure accurately particulate matter (PM) at low emission levels and assess their comparability with the standard laboratory instrumentation [3].
Several technologies and instruments are available and effort is ongoing to make these technologies more compact and suitable for on vehicle testing. Candidate PEMS instruments within the PM PEMS program includes: SEMTECH PPMD, Control Sistem m-PSS, AVL Micro Soot Sensors (MSS), Dekati Mass Monitor (DMM) and Electrical Tailpipe PM Sensor (ETaPS), Horiba On board System Transient PM Mass Measurement (OBS TRPM) [3,7].

This paper presents the SEMTECH PPMD by Sensors, based on the quartz crystal microbalance (QCM) technique for low PM mass measurements, typical of DPF equipped engines, and meeting the US Not to Exceed (NTE) regulation requirements. The SEMTECH PPMD uses the exhaust mass flow meters (EFM) equipped with differential pressure devices and thermocouples to obtain the exhaust mass flow and temperature and it is composed of two micro-proportional sampling systems (MPS) for exhaust dilution and a carousel quartz crystal microbalance (CQCM), consisting of eight piezoelectric crystals, for particulate mass collection. A description and illustration of the SEMTECH PPMD components is provided with focus on the dilution system (MPS) and the carousel QCM [4].

Figure 1 illustrates the MPS design together with the overall PPMD internal components [4,5]. The second MPS is to allow for additional dilution. The initial dilution is at the downstream end of the sample inlet capillary (for capillary flow control). The second is at the upstream end of a venturi throat (downstream of the transport capillary containing the sample and primary dilution). This secondary dilution creates a pull or suction on the end of the second or transport capillary. The sample capillary flow control dilution (or primary dilution) is at a pressure higher than the venturi (secondary) dilution point. The equations for the flow through the sampler can be determined by applying Bernoulli's equation along with the requirements of constant total flow and the sample flow must be proportional to the exhaust flow. Figure 2 shows the Carousel QCM with the 8 piezoelectric crystals and its working principle according to the QCM theory based on the frequency to mass relationship as defined according to the Sauerbrey fundamental equation [6]. Thus, the particulate mass collected on the crystal can be determined by measuring the change in the crystal natural frequency as:

$$(\Delta f)/(\Delta m) = -C_f / A_d \qquad \text{(i)}$$

$$\text{for } A_d \geq A_a \quad C_f = f^2/Nq \qquad \text{(ii)}$$

Where f = crystal resonant frequency; Δf = change in frequency due to a change in mass per unit area on the crystal; q = density of the quartz; N =frequency constant for AT-cut quartz; C_f = sensitivity;

A_a= active (or vibrating portion) of the crystal surface, A_d = area covered by deposit Δm.

The SEMTECH PPMD system determines mass over NTE events or other user-defined sample intervals with resolution less than 2 nanograms by measuring the mass before and after the sample interval. This method most closely simulates the standard gravimetric sampling method, where filters are allowed to equilibrate with a standard condition
As candidate PEMS, it is evaluated under controlled laboratory conditions on reference test cycles, such as the World Harmonized Transient Cycle (WHTC), against reference laboratory instruments based on gravimetric methods, using the conventional Constant Volume Sampling (CVS) and partial flow sampling (PFS) principle for dilution.

Preliminary SEMTECH PPMD results from the EU PM PEMS program are reported. The European Commission PM PEMS program includes 3 laboratory testing phases using different engines running on low sulfur fuel (S < 10 ppm) [7]:
1) Phase I - Euro III (IVECO Cursor, 10.6 litre); 2) Phase II - Euro V (MAN 10 litre, no DPF); 3) Phase III - US2007 engine with DPF.
Data reported refer to Phase II. Figure 3 shows the experimental set-up at JRC for the PM PEMS laboratory evaluation of the candidate PM PEMS instruments; these are the SEMTECH PPMD, Control Sistem m-PSS, AVL Micro Soot Sensors (MSS), Dekati Mass Monitor (DMM) and Electrical Tailpipe PM Sensor (ETaPS), Horiba On Board System Transient PM Mass Measurement (OBS TRPM) [3,7].
Figure 4 reports PM mass (g) as function of time (s) over the WHTC cycle for three tests as mass accumulated on crystals. Figure 5 shows the total PM mass (g/test) over 15 WHTC cycles (direct measurements) and over 11 WHTC cycles with heated extension line (5 meter) (righty-axis) and PM mass accumulated on crystals (ug) (left y-axis). Figure 6 compares the total PM mass (g/KWh), recorded with the SEMTECH-PPMD and the reference laboratory gravimetric method (CVS and SPC) (g/KWh) over the EU V engine (Phase II). Good agreement was found over hot WHTC cycles; data reported for the SEMTECH-PPMD are not corrected for losses.
The SEMTECH-PPMD, based on the QCM technique for PM mass measurement in continuous, has shown promising results as candidate PM PEMS in the first two phases of the EU PM PEMS program (Euro III & Euro V engines). Good agreement with the standard gravimetric method (CVS & SPC) was found over hot WHTC cycles. Further data analysis is on-going. The final phase of the EU PM PEMS program, using a US2007 engine equipped with DPF is going to start shortly. Data will be presented in the near future.

1) *L. Rubino, P. Bonnell et al. "Development of an official test method for on-board PM measurements from Heavy-Duty diesel engines in the European Union", SAE paper No. 2007-01-1946, 2007.*
2) European Project on Portable Emissions Measurement Systems: "EU-PEMS" Project: Status and Activity Report 2004-2005, January 2006, EUR Report EUR 22143 EN.
3) *EU PEMS PM Evaluation Program-Call For Interest [http://ec.europa.eu/enterprise/automotive/pages background/pems_project.htm].*
4) *D. Booker, R.A. Giannelli, and J. Hu, "Road Test of an On-board Particulate Matter Mass Measurement System", SAE 2007-01-1116.*
5) *J.E. Brockmann, B.Y.H. Liu, P.H. McMurray, "A Sample Extraction Diluter for Ultrafine Aerosol Sampling", Aerosol Science and Technology, vol 3-4, pp441-451 (1984).*
6) *Sauerbrey, G.Z.: Measurements of the amplitude distribution of vibrating AT-cut crystals by means of optical observations Proc. Of the 17th frequency control symposium (1963)*
7) *L. Rubino, P. Bonnel et al., "Portable Emission Measurement System (PEMS) For Heavy Duty Diesel Vehicle PM Measurement: The European PM PEMS Program" SAE No. 09ICE-0015 in press.*

Portable Emission Measurement Systems (PEMS) for Heavy-duty Diesel Vehicles PM Measurements: the SEMTECH Portable Particulate Measuring Device (PPMD) and the EU PEMS Program Experience

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Sensors Europe GmbH, Feldheider Str. 60, 40699 Erkrath, Germany

INTRODUCTION

• Portable Emissions Measurement Systems (PEMS) represent a robust and accurate solution to study the in-use emissions of combustion engines.

• While PEMS instrumentation and the test methods are mature for gaseous emissions, the development of portable PM instruments and their test protocols remain a challenge, as simultaneous progress take place in the engine and after-treatment technology [1].

• PM PEMS instruments are currently under evaluation within the European Commission EU PM PEMS program to check their feasibility to measure accurately particulate matter (PM) at low emission levels and assess their comparability with the standard laboratory instrumentation [2, 6].

• Candidate PM PEMS instruments are: Sensors SEMTECH-PPMD, Control Sistem m-PSS, AVL Micro Soot Sensors (MSS), Dekati Mass Monitor (DMM) and Electrical Tailpipe PM Sensor (ETaPS), Horiba On Board System Transient PM Mass Measurement (OBS TRPM) [6].

• The SEMTECH-PPMD by Sensors, based on the Quartz Crystal Microbalance (QCM) technique for low PM mass measurements is presented. Preliminary results from the EU PM PEMS program are shown.

SEMTECH-PPMD & SET-UP

• The SEMTECH-PPMD by Sensors is based on the QCM technique for continuous PM mass measurements under real-world conditions, with nano-grams sensitivity [3, 6]. It uses the Exhaust Flow Meter (EFM), equipped with differential pressure devices and thermocouples to obtain the exhaust mass flow and it is composed of:

- Two Micro-Proportional Sampling (MPS) systems for sample exhaust dilution (dual stage dilution);

- Carousel Quartz Crystal Microbalance (CQCM) consisting of eight quartz crystals for particle mass collection.

Figure 1 shows the overall system components (a) and the MPS design for sample dilution (b).

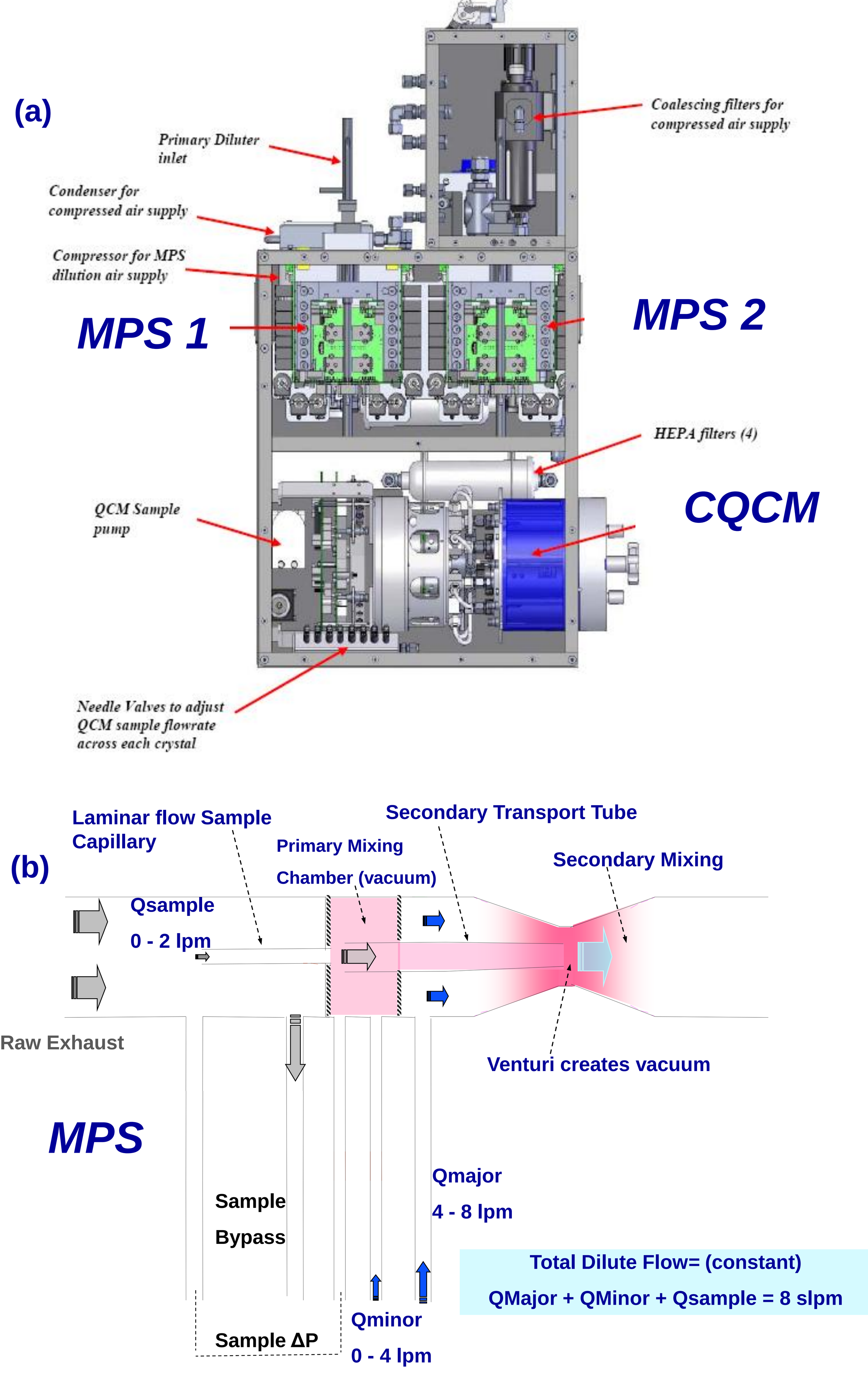

Figure 1: SEMTECH-PPMD components (a); schematic of MPS design for sample dilution (b) [3,4].

SEMTECH-PPMD & SET-UP

• The QCM technique employs a piezoelectric crystal as a sensitive microbalance. Electrostatic precipitation collects aerosol particles on the surface of the piezoelectric crystal, the crystal is excited in its natural frequency, which decreases with increasing mass load on its surface; the crystal frequency to mass relationship is defined by the Sauerbrey fundamental equation as [5]:

$$(\Delta f)/(\Delta m) = -C_f / A_d \qquad \text{(i)}$$

$$\text{for } A_d \geq A_a \qquad C_f = f^2/Nq \qquad \text{(ii)}$$

f = crystal resonant frequency; Δf = change in frequency due to a change in mass per unit area; q = density of the quartz; N =frequency constant for AT-cut quartz; C_f = sensitivity; A_a= active (or vibrating portion) of the crystal surface, A_d = area covered by deposit (Δm).

• The SEMTECH-PPMD measures PM mass continuously by switching to the next available crystal of the CQCM (one crystal is used as reference). PM is calculated by measuring the mass before and after a sample interval of around 120 s.

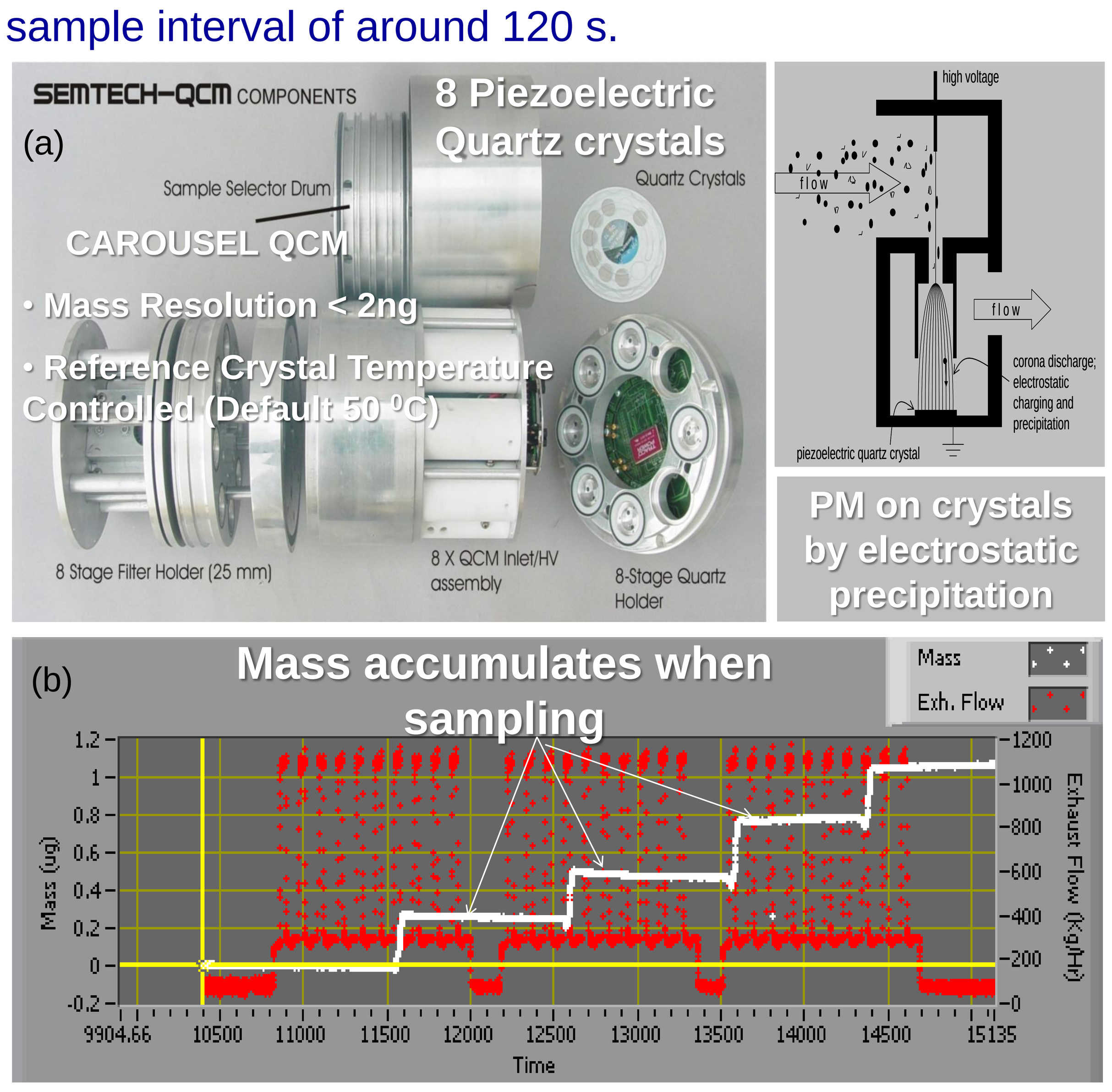

Figure 2: SEMTECH-PPMD Carousel QCM (a). PM mass accumulated (ug) on crystals during operation (b).

• The European Commission PM PEMS program includes 3 laboratory testing phases using different engines running on low sulfur fuel (S < 10 ppm) [6]:
1) Phase I - Euro III (IVECO Cursor, 10.6 litre); 2) Phase II - Euro V (MAN 10 litre, no DPF); 3) Phase III - US2007 engine with DPF.

• The SEMTECH-PPMD as candidate PM PEMS was tested over the WHTC cycle and compared to the standard gravimetric method using the Constant Volume Sampling (CVS) for dilution and the partial flow sampling system (PFSS) where PM was collected on a PallflexEMFABTX40HI20, 47 mm diameter. The experimental set-up for the SEMTECH-PPMD and the other candidate PM PEMS is shown in Figure 4.

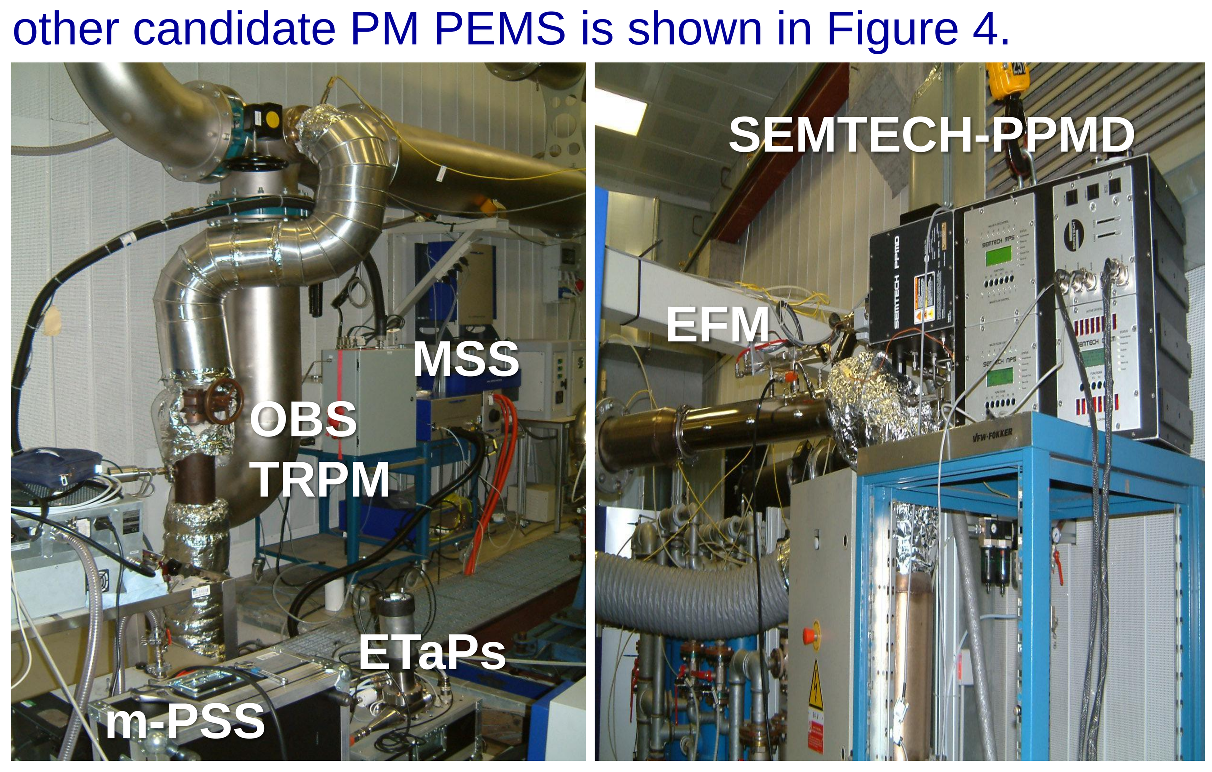

Figure 3: Laboratory experimental set-up for SEMTECH-PPMD and PM PEMS candidate instruments at JRC (VELA).

RESULTS

• Preliminary SEMTECH-PPMD results from the first two phases of the EU PEMS program are presented;

• PM measurement as mass accumulated on crystals (g) over the WHTC cycle is shown in Figure 4; total PM mass (g/test) over the WHTC cycle using the EU V engine (MAN, 10 litre) (Phase II) is shown in Figure 5. Comparison among the standard gravimetric method (CVS and SPC), for PM measurements and the SEMTECH-PPMD PM (g/KWh) is shown in Figure 6 .

RESULTS

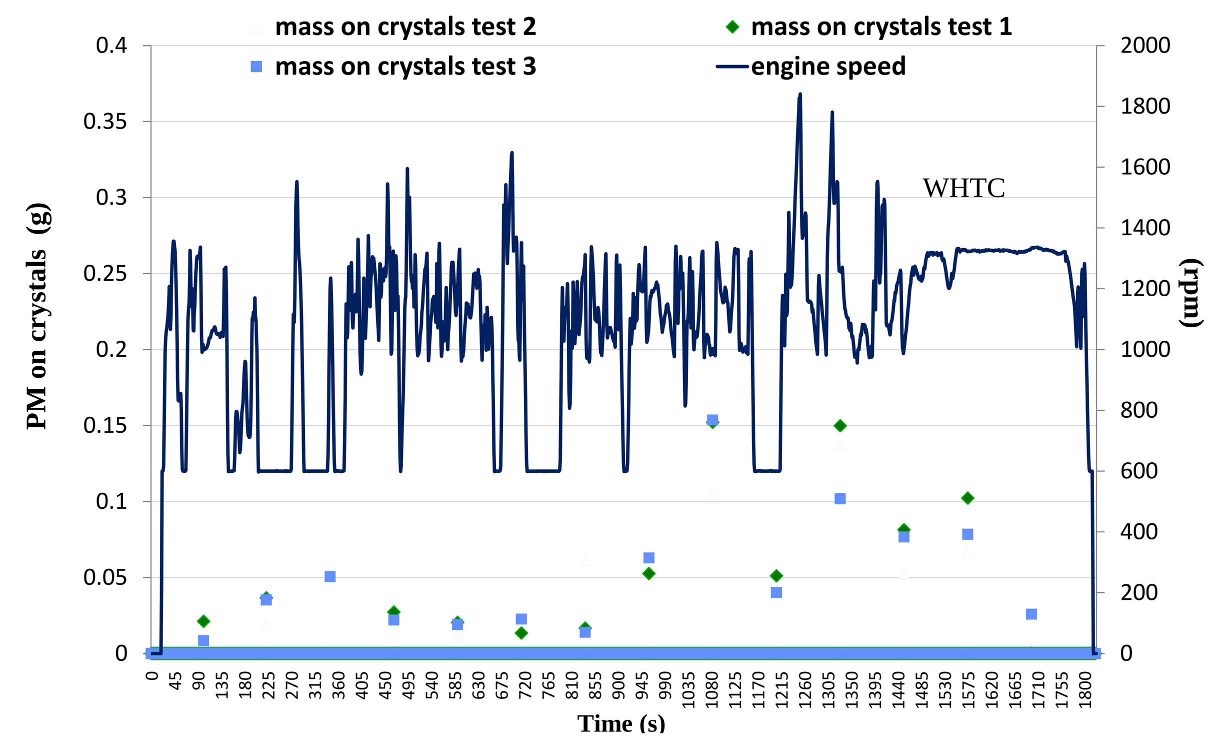

Figure 4: PM mass measurements (as mass accumulated on crystals g) over the WHTC cycle.

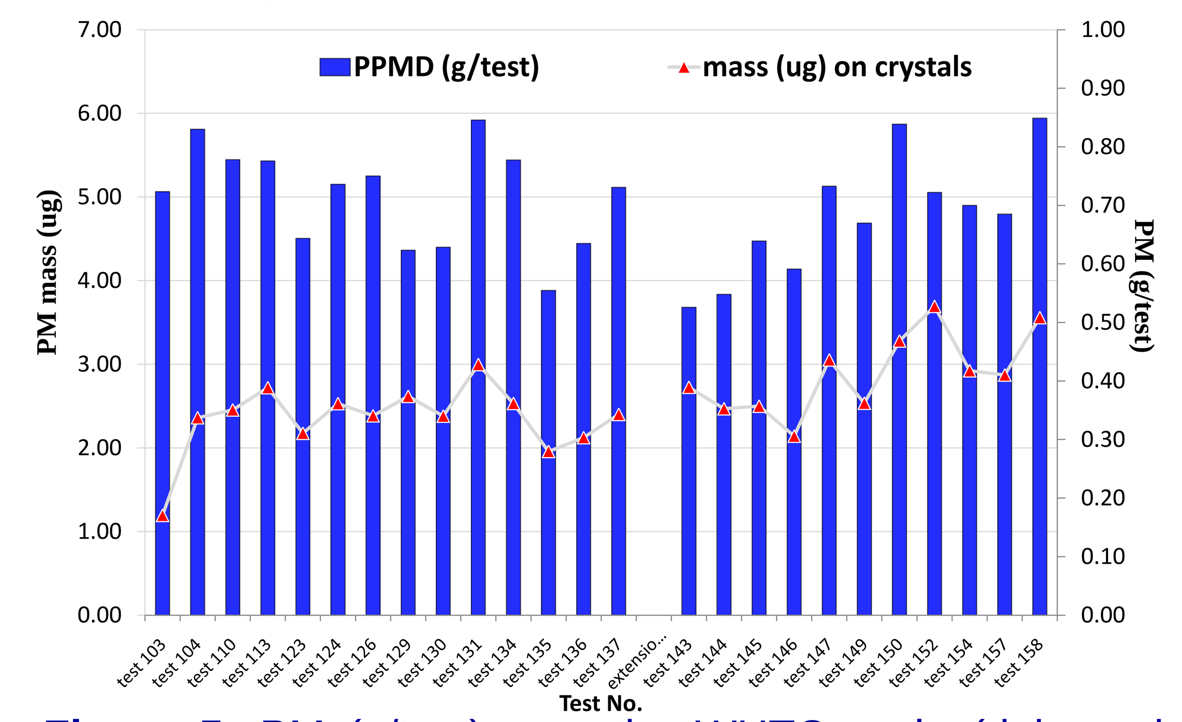

Figure 5: PM (g/test) over the WHTC cycle (righty-axis) and PM mass accumulated on crystals (ug) (left y-axis) - Euro V engine investigation (phase II).

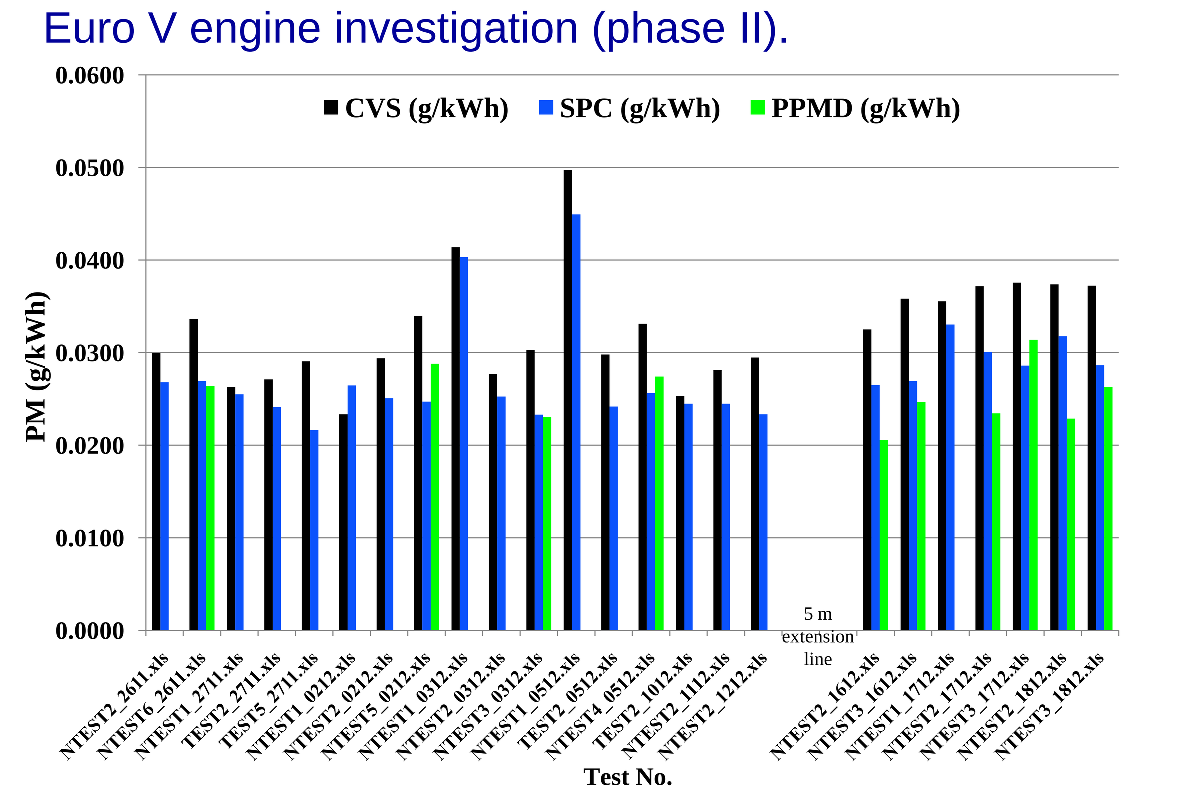

Figure 6: Comparison among CVS, SPC and SEMTECH-PPMD PM mass measurement (g/KWh), EU V engine (Phase II); PPMD data not corrected for losses.

CONCLUSIONS

• The EU PM PEMS program consists of 3 phases, in which different engines and after-treatment technologies, fuels and duty cycles are used to check the response of PM PEMS candidate instruments. The objective is to check their feasibility to measure accurately particulate matter (PM) at low emission levels and assess their comparability with the standard laboratory instrumentation.

• The SEMTECH-PPMD, based on the QCM technique for PM mass measurement in continuous, has shown promising results as candidate PM PEMS in the first two phases of the program (Euro III & Euro V engines) over the WHTC cycle, running on low sulfur fuels.

• Good agreement with the standard gravimetric method (CVS & SPC) was found over hot WHTC cycles. Further data analysis is on-going. The final phase of the EU PM PEMS program is ongoing.

REFERENCES

1) L. Rubino, P. Bonnell et al. "Development of an official test method for on-board PM measurements from Heavy-Duty diesel engines in the European Union", SAE paper No. 2007-01-1946, 2007.
2) EU PEMS PM Evaluation Program-Call For Interest [http://ec.europa.eu/enterprise/automotive/pages background/pems_project.htm].
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4) J.E. Brockmann, B.Y.H. Liu, P.H. McMurray, "A Sample Extraction Diluter for Ultrafine Aerosol Sampling", Aerosol Science and Technology, vol 3-4, pp441-451 (1984).
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CONTACTS

Dr. Lauretta Rubino – Sensors Europe GmbH

Tel: +49(0)21041418876 - Email: lauretta.rubino@sensors-europe.eu