PROJECT SUREAL-23 (GA:724136)
UNDERSTANDING, MEASURING AND REGULATING SUB-23 NM PARTICLE EMISSIONS FROM DIRECT INJECTION ENGINES INCLUDING REAL DRIVING CONDITIONS
Overview

- Project’s approach and objectives
- Main achievements
- Particle sampling and conditioning system
- Novel instrumentation
- Measurements
- What’ next
The Diesel Exhaust Aftertreatment (DEXA) Cluster (200-2005): A Systematic Approach to Diesel Particulate Emission Control in Europe
SUREAL-23 Approach

- **Objectives**
  - **Complement and extend** existing instrumentation for particles below 23 nm.
  - **Characterize** in detail the nature of the particulate emissions below 23 nm.
  - **Support future emissions** compliance through technical developments in RDE.

- **Innovation**
  - **Size and composition** analysis methods suitable for transient engine emissions.
  - **Novel instrumentation** for measuring aerosol particles below 23 nm, providing backward compatibility with established PN measurement technology.
  - Enhancement of instrument specifications to allow operation with **less demanding sample conditioning** requirements.
  - Integration of the most suitable components of the extended sub-23 nm measurement toolset into **PEMS** and verification in real driving conditions.

Joint Workshop, 9-10/10/2018
Technology Development and Testing

- **Sampling/Conditioning**
  - Standard PMP (with ET)
  - Advanced Catalytic Stripper (CS)
  - Flexible Sampling System

- **New Instrumentation**
  - Half Mini DMA
  - Induced Current Aerosol Detector (ICAD)
  - UV Photoelectric Charger (UV-PEC)
  - SL Multi-wavelength Photoacoustic Spectrometer (SL-MPAS)
  - Sizing CPC

- **Testing Platforms**
  - Standard particle generators (CAST, EAG)
  - Flex-fuel Engines
  - Engine and Vehicle dynos ( DIESEL and GDI)
  - Real Driving (PEMS)
Main Achievements (1/2)

- Significant breakthroughs have been realized regarding instrumentation.

  - Advanced HM-DMA
    - Unprecedented resolution and extremely fast response
    - Capable of hot measurements (minimal sampling requirements and also without the losses and artefacts)

  - Automotive ICAD
    - Fulfilled the requirements for sub-23 nm particle measurements
    - Very light and compact with small electrical power requirements, making it ideal for PEMS
    - Hot measurements (minimal sampling system).

  - The sizing-CPC, unique instrument, combining particle size with particle number concentration measurements was developed and currently validated in the lab.
    - Expected to bring unique capability in the measurements, also for PEMS.

  - The particle composition instruments (photoacoustic and photoelectric based) are currently validated.
Main Achievements (2/2)

- Advanced Sampling System and Nature of nanoparticles.
  - Sampling and Dilution Plan consisted of two pathways.
    - Eliminate a big part of the complicated PMP-like dilution system. Delivery of two instruments capable of hot measurements as already explained.
    - Development of an advanced dilution system, consisting of the typical two-stage diluters and the Volatile Particle Remover (VPR). Advanced design was followed based on an innovative ejector-type dilution system and a Catalytic Stripper (CS) as a VPR. The system has already been tested in the lab and engine exhausts showing minimal particle losses and artefacts for the sub-23 nm area and excellent volatile and sulphur removal efficiency.
The need for an advanced sampling and conditioning system

In some cases **artefact particles** are created while in other cases the VPR is unable to remove the volatile fraction completely.

Prototype **gasoline** engine: 250cc, 1cylinder, PFI/GDI, 4v, 24PS.

**G-DI**

![G-DI graph 1](image1)

![G-DI graph 2](image2)

**G-PFI**

![G-PFI graph 1](image3)

![G-PFI graph 2](image4)

CAST

M15 (15nm)
Sampling and Conditioning Particle System (SCPS)

➢ Design parameters

❖ Two-stage dilution, with adjustable dilution ratio (DR=30-120).
❖ Porous tube diluter as first stage to minimize sub-23 nm particle losses.
❖ Ejector diluter as a second stage to maintain stable DR under transient engine operation.
❖ Option for catalytic stripper/evaporation tube installation between the two dilution stages.

➢ Main project goals

❖ Minimum particle losses
❖ Artifacts elimination
❖ Dilution ratio stability and flexibility
❖ Compatibility with PEMS
The DR calculation is in excellent agreement with the DR calculated with the CO₂ measurement with the maximum difference being 6%.

The SCPS was employed at the raw exhaust of a GDI vehicle and maintained a very stable dilution ratio, DR=30±1.8%, during a NEDC.
The catalytic stripper fully oxidizes $>10^5$ (#/cm$^3$) tetracontane particles with $D \geq 30$ nm for space velocities up to GHSV 80000 or 25 lpm.

The maximum Sulphur adsorption capacity (>99.9% efficiency) is 7.3 mg or 0.31 g of S/lt of monolith. After regeneration the CS adsorbs 4.4 mg of S.
The SCPS tetracontane particle removal is tested in a wide DR range (30-60) and porous tube flow (12-35 lpm).

SCPS removes \(>10^6\) (#/cm\(^3\)) \(C_{40}H_{82}\) particles with >99% efficiency in all tested set points.

SCPS has a \(d_{50}=7.5\) nm, much lower than the current State-of-the-Art.

The SCPS particle number concentration reduction factor (PCRF) including PCRF\(_{15}\) is 1.15±9%.
The Advanced Half-Mini DMA (SEADM)

- **Half-Mini DMA** is a commercially available instrument that offers:
  - **High-resolution** size classification in the range 1-15 nm (use of electrometer by De la Mora *et al.*, 2017)
  - **Compactness** (2 cm working section)

**The concept**

**The design**

**The prototype**

- Source: SEADM

Advancements in the SUREAL-23 project

(HM-DMA → **Advanced** HM-DMA):

- **High resolution** in extended sub-23nm particle size range (5–30 nm)
- **Accurate hot operation up to 200°C** (Reduced exhaust aerosol conditioning, Measurements with a single hot dilution stage)
- **Fast response time** down to 1s for the extended size range.

The SUREAL-23 prototype
The Advanced Half-Mini DMA (APTL)

- Solid soot particle size distributions measured by SMPS and Advanced HM-DMA (hot operation) are in excellent agreement.

- The excellent agreement between the two measurements indicates that a single hot dilution stage can be used alternatively to the PMP-compliant VPR.
Coupling Advanced HM-DMA with a CPC to improve the detection limit, restricts the fast response advantage provided by the electrometer. Thus, coupling with a Fast CPC could enable measurement of aerosols with low particle concentration and it is under investigation.

**Experimental conditions:**
- 4-cylinder diesel engine, 190 cc of displacement
- Fuel w. CeO$_2$-based fuel additive
- HM-DMA hot operation (T = 150 – 165°C)
Transient measurements during an RTS95 driving cycle at GDI engine test bench

- HM-DMA (hot operation) + single stage hot dilution (DR~9)
- U-CPC + PMP-compliant, 2-stage dilution (DR~30)

High size resolution

At 22\textsuperscript{nd} sec. of RTS95 cycle
Main project goals

- Take an existing automotive partector (AP) and optimize settings to achieve a lower \(d_{50}\) cutpoint – \(d_{50}=10\)nm
- Operate device at high temperature to allow lower/no dilution – Operation \(T=150^\circ\)C
- Suitable for PEMS
Automotive ICAD evaluation

- ICAD counting efficiency & linearity evaluation was performed with mono- and poly-disperse CAST-generated particles.
- ICAD’s counting efficiency is similar to a CPC and $d_{50}=10$ nm.

- ICAD shows an excellent linearity against SMPS for a wide range of particle number concentrations, $10^4$-$10^6$ (#/cm$^3$).
Automotive ICAD hot operation

The proposed single hot dilution setup is tested with $5.5 \times 10^6$ (#/cm$^3$) $C_{46}H_{82}$ particles with $D_m \geq 30$ nm and shows removal efficiency $>99\%$ for $T \geq 150^\circ C$.

The diesel engine operates at low load (5% of full load) and the generated PSD has 20% in the sub-23nm size range.

Hot and cold ICAD measurements are in excellent agreement with SMPS, 1.9% and 3.7% respectively.
Automotive ICAD hot operation & response time

- Automotive ICAD and a CPC ($d_{50}=2.5$ nm) were employed for particle number measurements emitted by a G-DI engine during RTS95 cycle.
- Automotive ICAD measurements are in very good agreement with CPC under transient conditions (~12% difference).
Sizing CPC

◷ Objectives

❖ Develop a **standalone CPC** with particle **sizing capabilities without** the need of a mediating DMA
❖ **Optimized** function for sub-23nm particles
❖ **Robust** and **compact** instrument for PEMS implementation

◷ Principle of operation

❖ A N₂ flow (saturated with a low diffusive vapor) is mixed with the aerosol sample flow.
❖ In the **nucleator/booster tube**, the particles of the aerosol grow in size (through vapor condensation) until they reach optical detection size
❖ Particles are counted at the optical module
❖ Fine **control of N₂ flow** determines the critical value of the vapor saturation ratio (S) that dictates the smallest particle size that can be detected after growth
❖ **Sweeping through a range of S values** a size distribution can be obtained
Sizing CPC

Future work

- Further validation of resolution, accuracy, repeatability, linearity with reference devices, diesel & gasoline engines
- Evaluation of different nucleation solutions: Butanol, Nonane
- Further development for higher TRL level and PEMS implementation
UV Photoelectric Charger (UV-PEC): Principle of operation

- When an aerosol is irradiated with ultraviolet (UV) light of energy above the photoelectric threshold of **surface material**, electrons may be emitted / particles acquire a positive charge.

- The photoionization threshold is strongly **material dependent** can be used to distinguish the chemical fingerprint of condensed matter on the exhaust particles.

- Basic components:
  - Electrostatic precipitator
  - UV light source (200-400 nm)
  - Ionization chamber
  - Ion trap (Optional for sub-23 nm particles)
  - Measurement device (Electrometer, CPC, SMPS)
The higher charging efficiency is observed at \( \lambda=206 \) nm.

The use of the catalytic stripper increases the signal due to the removal of the volatile substances (water, various hydrocarbons, etc.).

Charging efficiency and thus, PAH content, has a linear relation with the active surface area, \( S_A \):

\[
S_A(D_m) = \frac{12 \pi^2}{8.39 \xi} \frac{\lambda_g D_m}{C_1(Kn_m)}
\]

\( \xi = 1.36 \): constant that depends on the particle's nature
\( \lambda_g = 67 \) nm: mean free path of gas molecules
\( C_1(Kn_m) \): Slip correction or Cunningham factor
By adding a fuel additive or a lubrication oil, a second peak appears at sub-23 nm particles.

UV-PEC does not charge these sub-23 nm particles showing that no PAH exists on their surface.
SCL-MPAS: Principle of operation

- Components of an exhaust sample (gases, particles) that absorb pulsed light are heated and generate sound when they heat the gas around them.
- Generated sound is detected by amplifier/filter locked-in to the light pulse frequency.
- Technique measures mass concentration of absorbing substances.
- Basic components:
  - Pulsed light beam source (SCL)
  - Wavelength selection (monochromator)
  - Resonant photoacoustic cells
  - Microphone and pre-amplifier
  - Lock-in amplifier/filter
  - Photoacoustic signal acquisition
  - System control/monitoring electronics
SCL-MPAS: Instrument assembly

Monochromator

System control and data acquisition software

Microphone and pre-amplifier

Pulsed light beam source (SCL)

Resonant photoacoustic cell
SUREAL-23 indicative measurements

Diesel engine

Gasoline engine
Prototype DI/ PFI

Gasoline DI
Engine & Roller test bench

CNG engine test bench

In situ techniques
(particle number, particle size, composition)

Ex situ techniques
(morphology, composition)

➢ Engine related parameters
  ❖ Fuel injection strategy
  ❖ Engine speed
  ❖ Load

➢ Fuel related parameters
  ❖ Bio-fuel content
  ❖ High sulfur content
  ❖ Fuel additives
  ❖ Lubrication oil

➢ Exhaust after-treatment

➢ Special engine operating conditions

➢ Sampling / conditioning
For both fuels (gasoline, ethanol) Port Fuel Injection (PFI) emits far less sub-23 nm particles comparing to Direct Injection (DI).

For both fuels (gasoline, ethanol) and both injection strategies (DI, PFI) increased engine speed leads to increased emission of sub-23 nm particles.

Ethanol causes an decrease in sub-23 nm particle number concentration, however an increase in the sub-23nm fraction, in both DI and PFI configurations.
Addition of oxygenated biofuels generates more sub-23nm particle.

For RME50 at 1400 rpm the particle emissions increases with respect to RME100 likely because of the low injection pressure at this engine point.
Diesel sub-23nm particle emissions

4-cylinder diesel engine, 1900 cc of displacement

DPF regeneration

- During DPF regeneration two CPCs ($d_{50}=23$ nm, $d_{50}=2.5$ nm) measure downstream a CS, an ICAD measures after a hot dilution and EEPS without a VPR.
- Solid sub-23 nm are measured after the DPF regeneration that correspond to ~10% of the total particle number concentration.

Joint Workshop, 9-10/10/2018
Engine bench tests - Experimental setup

- Last generation of gasoline engine
  - Gasoline Direct Injection Engine w/Turbocharger
  - Volume displacement 1.3 L
  - Engine Power = 120 kW

- Tests matrix:
  - Tailpipe PN measurement w/ and w/o GPF
  - 3 driving cycles: WLTC, RTS95 and RTS95
    - Cold and hot start

- PN measurement devices: system: 3WC only
Engine test bench phase: Experimental setup

Reference instruments
- DMS-500
- FTIR

Exhaust line

Prototype dual-stage diluter SCPS

Sampling tube

Prototypes instruments
- I-CAD
- HM-DMA

Refrence instruments
- SMPS-1
- SMPS-2
- AE-33
- CO2
- DR meas.

Joint Event, 9-10/10/2018
Experimental setup in the test cell
Engine test bench phase: focus on results w/ & w/o GPF

- Example of RTS95 cycle, cold start

<table>
<thead>
<tr>
<th>Part/km</th>
<th>Upstr. GPF</th>
<th>Downstr. GPF</th>
<th>GPF eff.</th>
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<tbody>
<tr>
<td>ICAD</td>
<td>2.97E+13</td>
<td>3.82E+12</td>
<td>87.1%</td>
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<tr>
<td>CPC3775</td>
<td>3.33E+13</td>
<td>3.15E+12</td>
<td>90.6%</td>
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<tr>
<td>CPC3776</td>
<td>1.56E+13</td>
<td>1.52E+12</td>
<td>90.3%</td>
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<tr>
<td>DMS500</td>
<td>2.93E+13</td>
<td>2.93E+12</td>
<td>90.0%</td>
</tr>
<tr>
<td>AE33 (ng)</td>
<td>4.9</td>
<td>0.9</td>
<td>82.2%</td>
</tr>
</tbody>
</table>
Engine test bench phase: focus on results w/ & w/o GPF

- Half-Mini DMA & DMS500

**Half-Mini DMA**

- Qualitative ions concentration (μg/cm³)

**Upstream GPF**

**DMS500**

**Downstream GPF**

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 724136
Chassis dyno tests - Experimental setup

- Euro 6b vehicle: Audi 2.0L TFSI
  - 4 Cylinders Gasoline with Turbocharger
  - Dual injection system: Direct + indirect
  - Standard EATS system: 3WC only

- PN measurement devices
  - Prototypes: SUREAL-23 diluter + ICAD + HM-DMA
  - References: PMP + DMS 500
Chassis dyno tests – Test cell
Chassis dyno tests - Tests matrix

- **Parametric variations:**
  - 4 fuels: E10 (std), high sulfur content (150 ppm S), high aromatic content (39 %), E25
  - 2 lubricants: Audi 507 (low SAPS), Total Full SAPS (1.1%)
  - 3 driving cycles: WLTC, RTS95 and RTS95
  - Cold and hot start

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Lub.</th>
<th>WLTC</th>
<th>NEDC</th>
<th>RTS95</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Cold</td>
<td>Hot</td>
<td>Cold</td>
</tr>
<tr>
<td>E10</td>
<td>Low</td>
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<tr>
<td>High Aro</td>
<td>Low</td>
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</tr>
<tr>
<td>E25</td>
<td>Low</td>
<td>✓</td>
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<td>✓</td>
</tr>
<tr>
<td>E10</td>
<td>Full</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

- **WLTC Cold start**
ICAD and DMS

Euro 6c limit
Chassis dyno tests – Focus on High Aromatic Fuel

- Half-Mini DMA and DMS50
What’s next

- Continue testing with photoacoustic and photoelectric based instruments
- Continue measurement campaigns on chassis dynos
- PEMS integration
- On-road testing
Conclusions

- Current regulations miss an important and variable part of PN
- We can robustly measure solid sub-23 emissions
- Artefacts and losses are no longer obstacles not to account for sub-23 nm particles
- We should drive the regulation to sizes below 23 nm
- We should start considering alternative to PN metrics for the effective control of vehicle contribution to air-quality and health
Chassis dyno tests – PFI/GDI injection

WLTC cycle - Cold start - Fuel w/ high aromatic content - PN

3.58 $10^{13}$ part. (PFI)

2.25 $10^{13}$ part. (GDI)

1.6 time PN more in PFI mode ...

... but time passed in PFI is 2.8 time more