



*Understanding, Measuring and Regulating Sub-23 nm Particle Emissions from Direct Injection Engines
Including Real Driving Conditions*

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Abbreviations list

CPC	Condensation Particle Counter
CS	Catalytic Stripper
DC	Diffusion Charging
DMA	Differential Mobility Analyzer
DPF	Diesel Particulate Filter
DR	Dilution Ratio
EC	Evaporation Chamber
ET	Evaporation Tube
EU	European Union
GPF	Gasoline Particulate Filter
GDI	Gasoline Direct Injection
HM-DMA	Half-mini Differential Mobility Analyzer
ICAD	Induced Charge Aerosol Detector
ICE	Internal Combustion Engines
M	Month
PMP	Particle Measurement Programme
PN	Particle Number
PEMS	Particle Emission Measurement System
RDE	Real Driving Emissions
SMPS	Scanning Mobility Particle Sizer
SCPS	Sampling & Conditioning Particle System
VPR	Volatile Particle Remover
WP	Work Package



Short Project Overview

It is now known that a significant proportion of the total number of particles emitted from recently introduced direct injection engines have a size below 23 nm in diameter. Although the EU aims to regulate those emissions and impose limits on all new light-duty vehicles, this is not yet possible due to the absence of accurate quantification methods, especially under real driving conditions. The main reason for this is the lack of adequate knowledge regarding the nature of sub-23 nm particles from different engine/fuel combinations under different operating conditions. SUREAL-23 aims to contribute to overcoming this problem by introducing novel measurement technology for concentration/size/composition measurements. For laboratory / test cell studies, the recently established supercontinuum laser technology will be coupled to photoacoustic methods for composition-specific detection, while a controlled wavelength UV light source will be employed for photoelectric aerosol charging to achieve real-time, composition- and size-specific analysis of the particles. Additionally, state-of-the-art aerosol measurement techniques (electrical mobility spectrometry, electrical charge based PN counting) will be advanced for better compatibility with sub-23 nm exhaust particles also for RDE measurements. The developed instrumentation will assess sub-23 nm particle emissions from both Diesel and GDI vehicles, accounting for the effect of the fuel, lubricants, after-treatment and driving conditions for existing and near-future vehicle configurations. The most suitable of the concepts advanced in SUREAL-23 have been selected for PN-PEMS applications and evaluated accordingly.

Overall, the project aims to provide measurement technologies that will complement and extend established particle measurement protocols, sustaining the extensive investments that have already been made by industry and regulatory authorities. The ultimate project goal is the systematic characterisation of sub-23 nm particles in order to facilitate the formulation of future particle emission regulations as well as to assess any potential efficiency vs. emissions trade-offs in ICE technology developments.



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1 INTRODUCTION

The present document is supplementary to the delivered demonstrator “D5.1 PEMS-PN system”. In particular, this report survey SUREAL-23 project developments in Portable Emissions Measurement Systems (PEMS) suitable for real-time, on-board measurements of sub-23 particles emitted from engine exhaust during real driving conditions. This document summarizes the development, testing and validation of such instruments and pertains primarily to effort carried out within Task 5.1 of WP5.

2 STATE OF THE ART

Nowadays, regulations about particle emissions from light-duty, direct-injection gasoline and diesel engines is limited to particle diameter down to approximately 23 nm, as current PEMS do not detect exhaust particles below this size. Furthermore, the said PEMS units do not provide size-specific measurement of the exhaust particles, so their nature and origin under real-driving tests cannot be correlated to specific aspects of the fuel, lubricants, engine or exhaust after-treatment system. Therefore, there is a need of new instrumentation in order to define the regulations which will affect the next generation of light-duty vehicle engines.

Currently commercial available PN PEMS systems use two different technologies for particle measurement. The first category uses a Diffusion Charging (technology), the same as the ICAD operation principle. Most suppliers offer instruments featuring this type of particle measuring technique, which is robust, compact and lightweight, making it very suitable for PEMS applications. The second category uses a Condensation Particle Counter (CPC), frequently a modified variation of the typical laboratory instrument used for PMP-compliant measurements. One of the areas of modification is the working fluid or its container, since butanol – almost exclusively used in the laboratory – suffers from safety issues for on-board measurements.

At the moment, no supplier has a commercially available on-board instrument that includes a Differential Mobility Analyzer (DMA), which can provide data on particle size. Commonly this technique has low temporal resolution and is not inherently suitable for transient measurements, such as in real driving conditions. The Half-Mini DMA variant – considered in SUREAL-23 developments – is optimised for <30 nm particle diameter and brings advantages that allow a very fast size-scan of the sampled aerosol, and therefore providing the possibility for real-time size-spectra within the <23nm size range.

All instruments require a dilution system, able to lower the sample temperature and the maximum particle concentration to within the instrument limits, while avoiding condensation of volatile compounds. Both instruments described in the following sections can handle a hot (>150 °C) exhaust sample, bypassing the necessity of a Volatile Particle Remover (VPR), although a dilution stage may still be necessary to lower the maximum particle concentration that can be measured on non-DPF/GPF equipped vehicles or perhaps during DPF regeneration. This dilution stage will also provide a sample that is sufficiently hot, but not exceeding maximum acceptable temperature, which can often be the case with gasoline engines under heavy acceleration or high speed/load operation.

3 THE INDUCED CHARGE AEROSOL DETECTOR (ICAD)

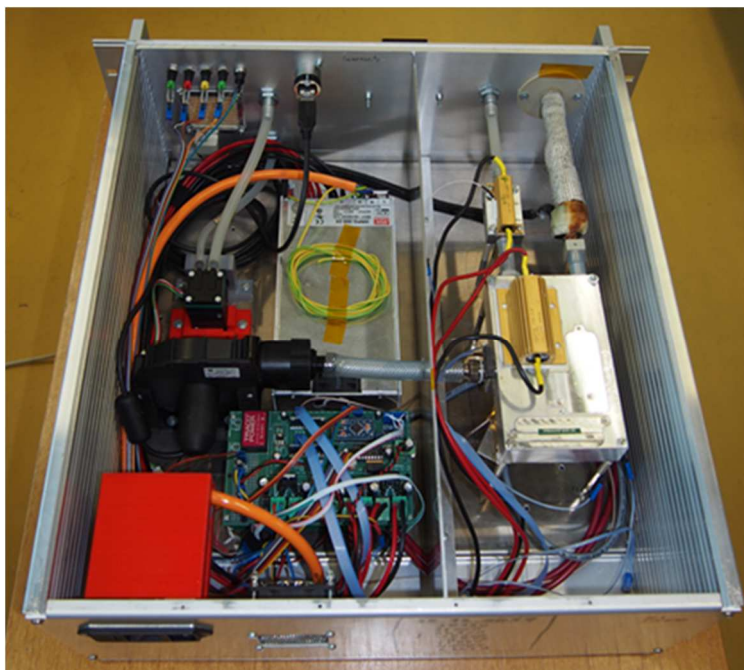


Figure 1 Photo of an open ICAD instrument

The ICAD instrument (Figure 1) consists of a unipolar diffusion charger that is followed by a pulsed electrostatic precipitator to remove a fraction of the particles and finally an induced charge detection stage to measure the removal of the particles in the precipitator. The induced charge detector stage produces very small signals, on the order of fA – pA, which must be measured by a very sensitive electrometer.

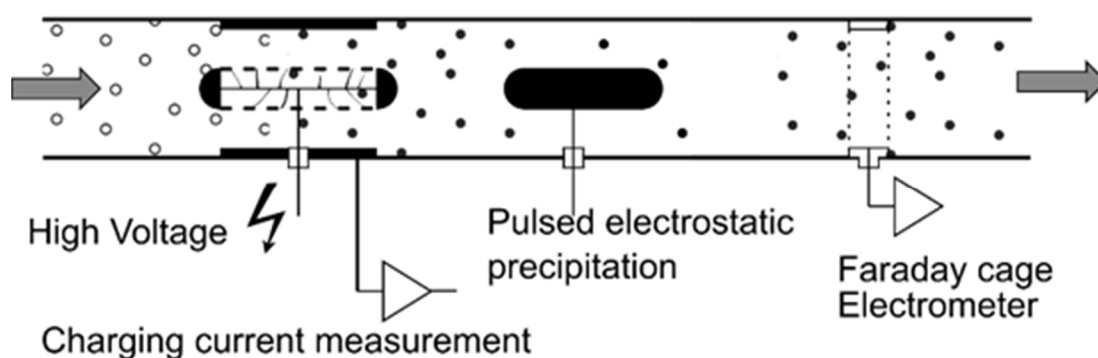


Figure 2 Operating principle of ICAD

Using a pulsed precipitator and an induced charge detection stage rather than measuring the charge from particles captured in a filter largely avoids issues with electrometer zero drift and filter clogging (Fierz et al., 2014) as an AC current is measured and virtually no particles are precipitated in the measuring stage (Figure 2). Within SUREAL-23 development efforts, the ICAD device has been tuned to achieve a cut-off of around 10nm and has been made tolerant of operating / sample temperatures up to 150°C. This allows an operation with only a very small or even no dilution. Figure 3 shows the counting efficiency as function of particle size. More details are available in Deliverable D2.3.

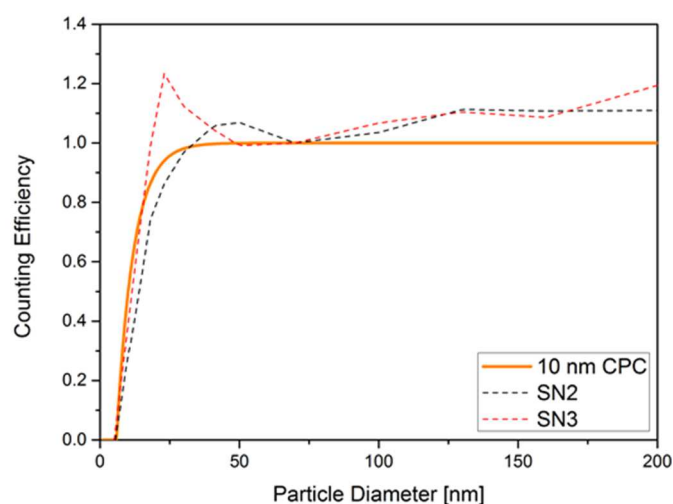


Figure 3 Normalized particle-counting efficiency of the two SUREAL prototypes compared to a hypothetical CPC with a 10 nm cut-off

4 HALF-MINI DIFFERENTIAL MOBILITY ANALYSER PEMS (HM-DMA PEMS)

4.1 Innovation

The Half-Mini DMA prototype instrument, described in Deliverable 2.4, performed well in engine bench trials, surpassing initial expectations of resolution and scanning speed. However, the initial prototype system was too voluminous to be deployed on-board, consumed excessive power and was not designed to work in an environment with intense vibration and inertial forces. Therefore, a series of modifications were implemented at the components integration level, mainly in order to miniaturize the instrument, but also assure robustness in such an inertially challenging on-board environment. The essential instrument architecture and core components were retained without modification.

The final volume of the whole HM-DMA based PEMS device was reduced by 17 times from the original prototype system volume (Figure 4). This reduction allows installing the HM-DMA PEMS in the trunk / baggage compartment of a sedan-type passenger car. The power consumption was reduced five times, from 2,600 W to 510 W. The on-board system is now powered from the vehicle battery (by means of a DC-to-AC inverter, as it still is AC-powered) and is grounded to the vehicle chassis.

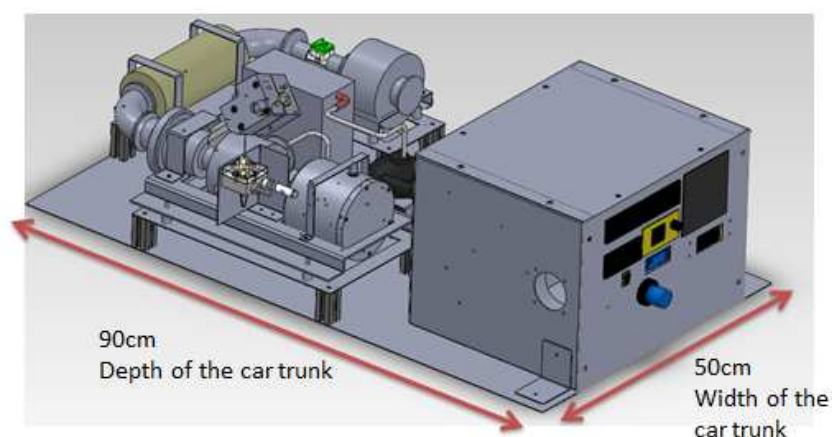


Figure 4 3D model of the Half-mini DMA for PEMS application.

Figure 4 shows the miniaturized instrument. The original blower, heater and cooler prototype subsystems were substituted by more compact units. The mobility cell [1-2], the HEPA filter, the ionizer and the electrometer [3] remained the same.

A custom-designed heater was constructed, based on a drilled heated block with flow cross-section of 15 mm². This solution reduced by 5 times the power consumption (from 1,000 W to 200 W) and by 40 times the heater volume. The ionizer and the transfer line also benefited from reduced power consumption of 3.6 times (100 W vs. 360 W) and 4 times (40 W vs. 160 W), respectively (Figure 5).

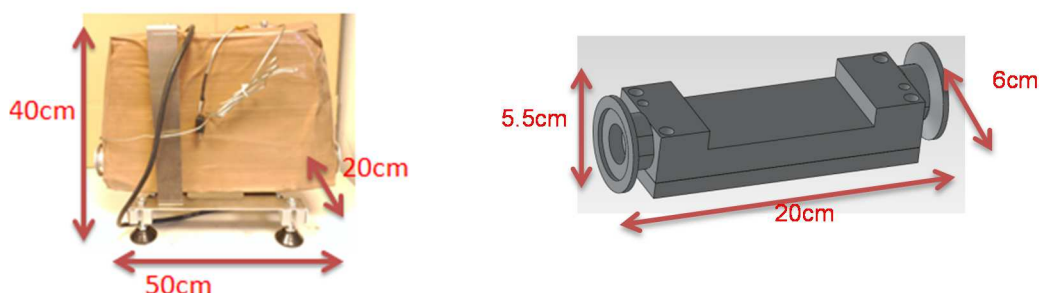


Figure 5 Left: original heater; right: new, miniaturized heater

The original cooler consisted of a passenger vehicle engine intercooler attached to a large fan. It was substituted by a natural-cooling, commercial item, resulting in a 20 times volume reduction and power of 35 W (Figure 6).

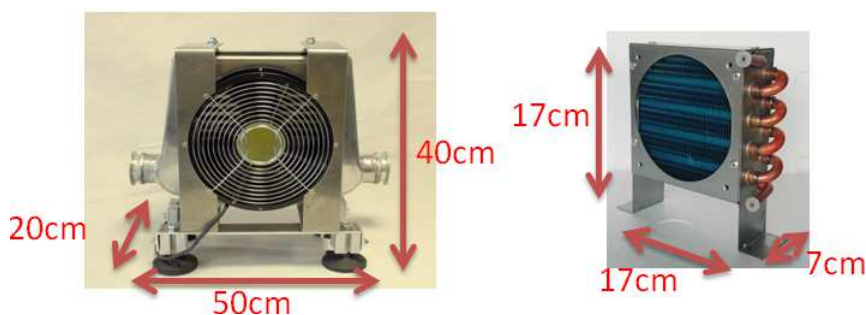


Figure 6 Left: original cooler; right: new, miniaturized cooler

A new control box (Figure 7) was designed in order to fit all the instrumentation within the least space possible. This control box features three temperature control channels (heater, ionizer and transfer line), the electrospray pressure and voltage control, electrospray current monitoring as well as sheath, sample and electrometer flow rate controls. It also features the DAQ system which allows software-control of most channels and acquisition of the output signal.



Figure 7 New control box for PEMS application

The whole system is assembled on a metallic structure supported by four anti-vibration supports, designed specifically for the weight of the system and to withstand and dampen the vehicle vibrations (Figure 8).



Figure 8 Anti-vibration supports

New instrument software was developed for the PEMS application. Besides specific input and outputs required for this application, audible alarms were implemented to assist the operators monitoring the instrument during on-road testing. The new software also provided additional data post-processing tools to facilitate the interpretation of the results.

4.2 Preliminary experiments

First tests aimed to characterize the stability of the new sheath flow blower. A simple, cold operation HM-DMA test bench was implemented. In order to reach high performance, the HM-DMA sheath flow must be very stable. This means that for a given flow rate setting, variations on the blower speed must be avoided, a factor which its control electronics are responsible for. The off-the-shelf / original blowers are typically not stable enough in their rotation speed (their own integrated electronics produce rough variations), so they need the external layer of finely-tuned control developed by SEADM in order to be suitable. The modified blower was subjected to stability tests, and compared with the original blower. Results showed that, for the blower model chosen, control enhancement were not needed as the flow stability with SEADM fine control was comparable to that of the original blower. Figure 9 shows a comparison of the flow rate during a ten second interval.

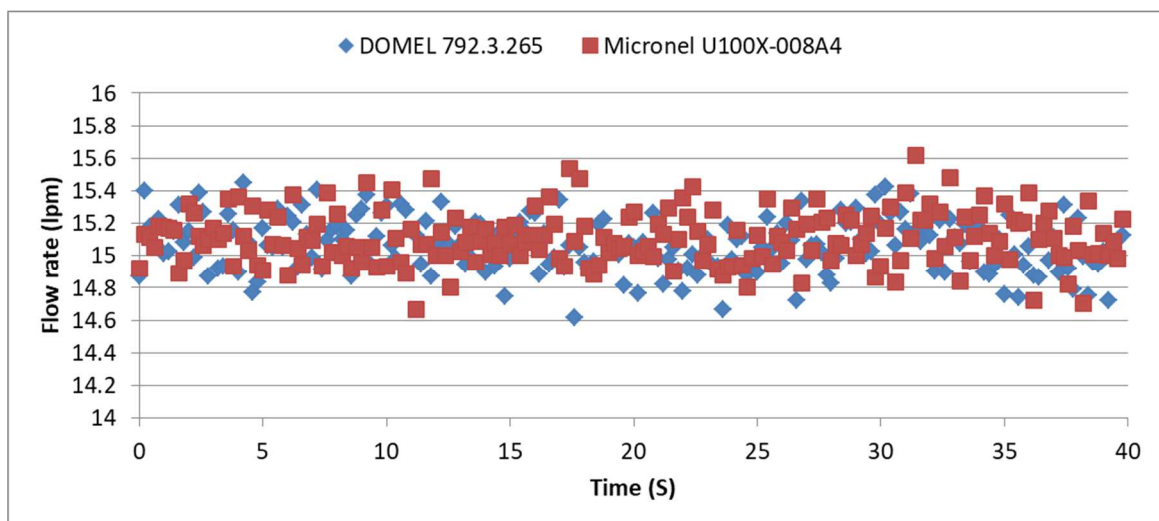


Figure 9 Stability test. Blue: DOMEL 792.3.265 (original blower with SEADM fine control); Red: Micronel U100X-008A4 (new, miniaturized blower).

A maximum Coefficient of Variation of 1.5% is allowed in order to assure high performance. For both blowers the CoV is around 1.1%, so the suitability of the new miniaturized blower was validated. Figure 10 shows a comparison of particle size spectra from tests with both versions of the control electronics where the comparable performance is evident as an absence of shift in particle size.

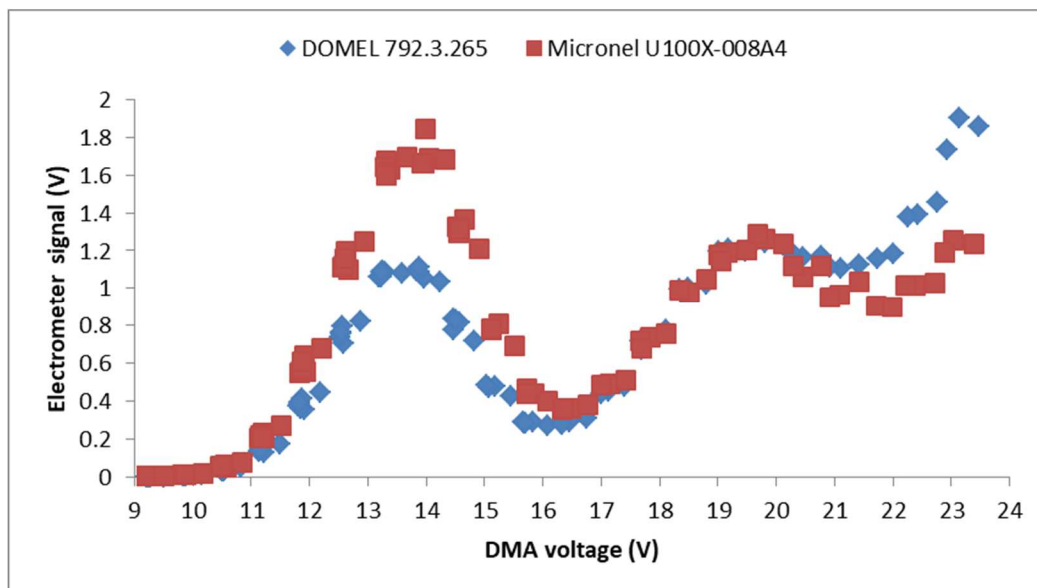


Figure 10 Spectra of THABr solution. Blue: DOMEL 792.3.265 (original blower with SEADM fine control; Red: Micronel U100X-008A4 (new, miniaturized blower).

After the validation of the new blower, the HM-DMA PEMS was assembled on a laboratory bench and tested at typical working settings (50 L/min sheath flow and sheath gas temperature at 200°C). The results of the usual validation and calibration test are shown in Figure 11, where the DMA voltage position of known ions THA^+ (monomer) and $[\text{THA}_2\text{Br}]^+$ (dimer) are taken as reference to calculate the mobility diameter.

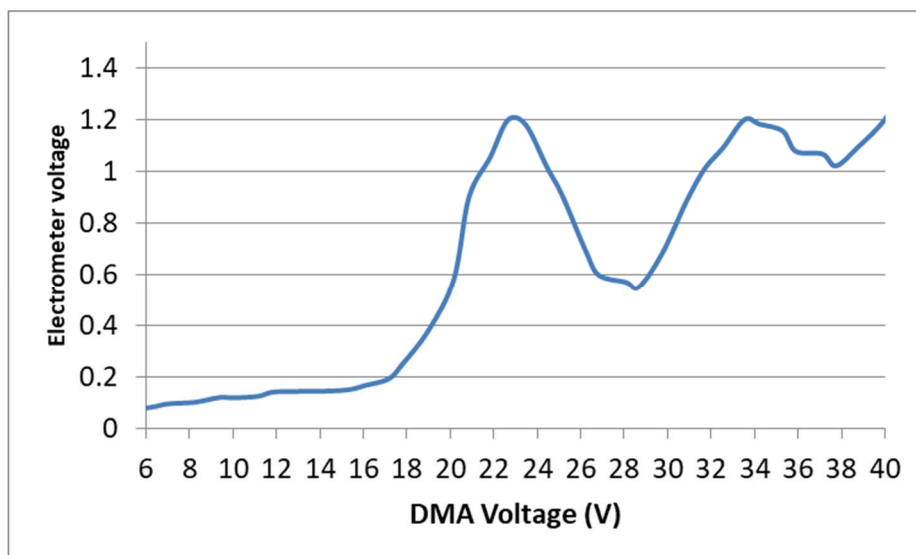


Figure 11 PEMS bench test THA^+ (monomer) and $[\text{THA}_2\text{Br}]^+$ (dimer) peaks are identified at ~23 V and ~34 V, respectively.

On the next step, a test vehicle was adapted to install the PEMS and test its performance on a moving platform. The test vehicle was a Fiat Ducato van (Figure 12). Middle and back seat rows

were removed to make room for the prototype HM-DMA PEMS, which was rigged to the floor by means of military-grade Velcro straps. An air storage buffer was added only for sample flow calibration tests, as during real experiments it will be substituted by the sampling system.

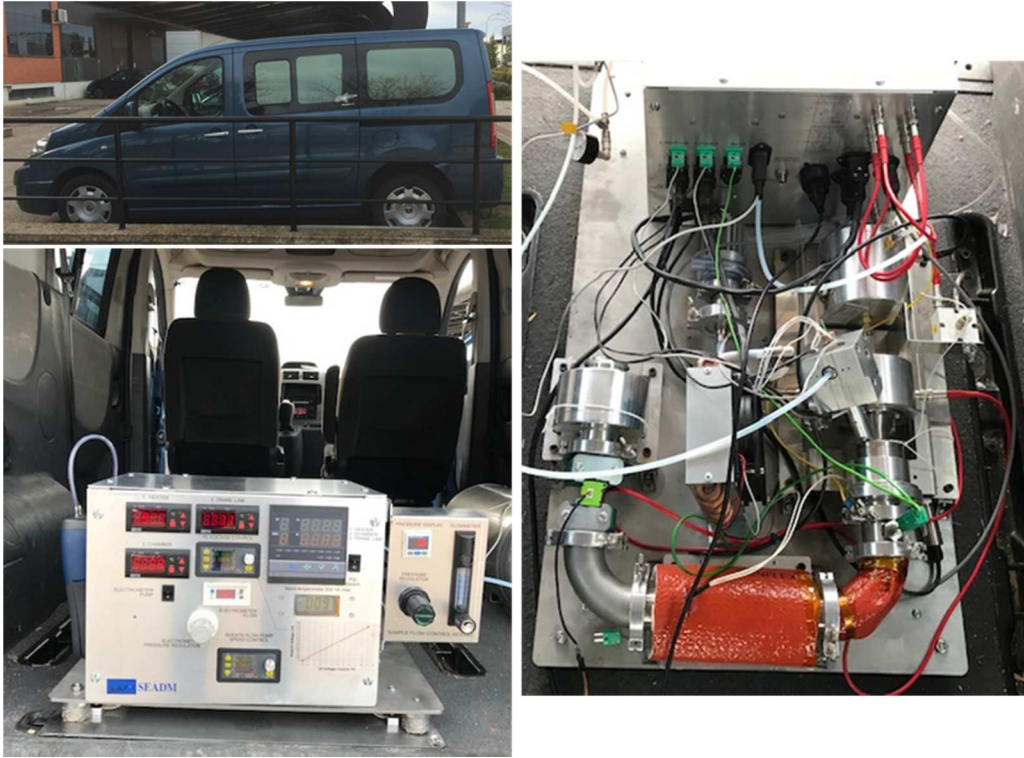


Figure 12 PEMS rigged to test vehicle.

Finally, the next battery of tests aimed to study the HM-DMA PEMS performance when the system is working inside a moving vehicle. At the beginning the reliability of the electrometer operating under vibrating environment was tested. Its noise signal was recorded continuously while driving in urban environment (50 km/h), around SEADM facilities. The anti-vibration supports were quite effective in eliminating noise sources. The electrical noise recorded on the electrometer was in the order of tenths of millivolts, as is seen in laboratory conditions.

5 SAMPLING SYSTEM

Even though the PEMS instrumentation, developed during the SUREAL-23 project, includes significant advances to enhance performance for on-board emission measurement applications, preliminary tests in passenger cars indicated that dilution of the sample cannot be avoided in all cases. More specifically, in GDI engine equipped cars, with no GPF installed, particle concentration levels in the exhaust gas can exceed the maximum limit of the instrumentation.

The Sampling and Conditioning Particle System (SCPS) developed during the project has already been evaluated and has shown robust operation under laboratory conditions, however, its electrical power and compressed air requirements render it unsuitable for PEMS applications. As a result, a new, portable dilution system with drastically reduced power requirements is required for on-board operation in light duty vehicles and provide appropriately conditioned exhaust flow sample to the PEMS instrumentation.

In order to drastically reduce power consumption, the heated parts of the system have to be minimized or removed altogether, since electrical resistors and heating elements are the major power consumers in such systems. Nevertheless, in order to reduce the particle concentration

of the exhaust sample, the dilution air has to be at approximately the same temperature as the raw sample, to avoid condensation and therefore effects on the particle measurements. Additionally, compressed air is usually not available in on-board applications, especially in passenger cars. Utilizing an air compressor, increases power consumption prohibitively, requires significant additional space and introduces other issues such as noise suppression. On the other hand, the alternative option of using high pressure gas bottles to carry compressed air raises issues of on-road safety and of available on-board space. Particularly in A-segment or B-segment passenger cars, the space available is not sufficient for gas bottles of a volume that can support reasonable on-road test durations. The smaller bottles that can typically be accommodated on-board would need to be upsized by a factor of 3 or so in order to provide enough air for dilution purposes. Irrespective of space limitations, the high pressure air storage (and refilling) would be a relatively costly solution for the supply of dilution air for on-board instruments.

A relatively simple solution to the aforementioned on-board power/space issues is to use a stream of the exhaust flow itself as dilution gas, after filtering all particles from it. The following Figure 13 illustrates the operating principle of the low power PEMS diluter developed within Task 5.1:

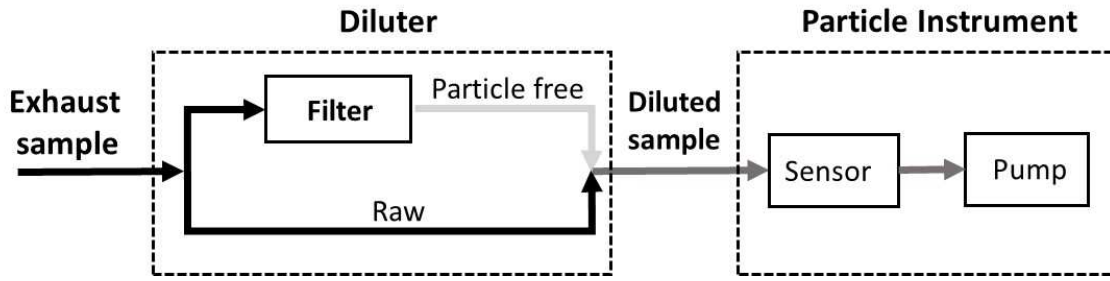


Figure 13 Schematic of PEMS dilution system

A sample flow from the tailpipe is split into a filtered and an unfiltered stream. The filtered stream, free from particles, is then mixed with the unfiltered (“raw”) stream. The filter used is a high efficiency filter, allowing only particle-free gas to come out. Both streams are maintained at the same temperature since the entire device is compact and thermally well insulated. The device operates on a passive principle whereby the dilution ratio (DR) is determined by the flow resistances in each of the two flow paths (raw and filtered). By varying the tube diameter of the raw stream branch and the size/permeability of the filter of the dilution stream, the DR can be modified, according to the requirements of the measurement setup. A DR of the order of 10:1 is usually sufficient to keep the maximum particle concentration within the instrument limits and can be easily achieved with this kind of a dilution system. The DR can be determined by the selection of the geometric and material characteristics of the raw sample tubing and the filter by the following equation [4]:

$$DR = \frac{128L_n}{\pi D^4} \frac{kA}{L_f} + 1$$

where L_n is the length of the raw stream tube, D is the diameter of raw stream tube, L_f is the length of the dilution stream filter, A is the filter cross-sectional area and k is the effective/bulk permeability of the filter volume. The above assumes a round cross-section for the raw stream tube.

The dilution system can be attached in close proximity to the tailpipe or tailpipe extension, typical in PEMS installations, to minimize particle losses. The tube connecting the system to the measuring instrument should be heated, to avoid thermophoretic losses of particles to the tube wall. Transfer tubing length should be kept to the minimum possible in order to reduce

particles losses as well as power consumption. This can vary depending on the vehicle under test.

The PEMS diluter was designed and manufactured to perform well in PEMS applications, but it can also be of use in other sampling applications, especially in cases where there are restrictions in compressed air supply and available electrical power.

Evaluation of the diluter system will take place during T5.2, along with the other PEMS instruments, under real driving conditions.

6 CONCLUSIONS

The requirement of demonstrating new sub-23 nm particle instrumentation for RDE measurements was satisfied by the adaptation of the ICAD and HM-DMA prototype instruments. . The PEMS based on the HM-DMA, which will be delivered to APTL in January 2019 for evaluation tests, has undergone major adaption from the first laboratory prototype (from WP2) in order to work as a fully portable / on-board system, allowing size classification of exhaust nanoparticles below 1-30 nm. The bulkiest elements from the laboratory HM-DMA instrument were drastically miniaturized and their power consumption substantially reduced, such that the resulting prototype has demonstrated the capability to be easily rigged on a test vehicle. On-road verification tests run with artificially generated reference aerosols, while driving, have shown reliable performance despite working in a vibrating environment.

The ICAD instrument, in its laboratory prototype format, already fulfilled most PEMS requirements and relatively minor modifications were required, primarily to increase robustness. Next steps will include the instrument evaluation and testing on real-driving test and the provision of feedback for any new changes required.

Major adaption was also needed for the dilution system intended for bringing exhaust particle concentrations to within instrument upper limits. The portable sampling system that was designed is a new concept, featuring very low power consumption and the absence of dilution air supply requirements, therefore, ideally suited for PEMS application. The evaluation phase that follows Task 5.1 will provide additional valuable feedback for any necessary modifications, either to adjust DR of the sampling to better match instrument specifications or to increase robustness and stability.

7 REFERENCES

1. Fernández de la Mora J., Kozlowski J., Hand-held differential mobility analyzers of high resolution for 1–30 nm particles: Design and fabrication considerations. *Journal of Aerosol Science* 57 (2013) 45–53
2. Fernández de la Mora J. Expanded size range of high-resolution nanoDMAs by improving the sample flow injection at the aerosol inlet slit. *J. Aerosol Science*, 113 265-275. Nov 2017.
3. Fernandez de la Mora J., Perez-Lorenzo L.J., Arranz G., Amo-González M., Bertscher H. Fast high-resolution nanoDMA measurements with a 25 ms response time electrometer *Aerosol Science and Technology*, accepted for publication (Jan 2017).
4. Bainschab, M., Bergmann, A. An Intrinsically Pressure Insensitive Low Cost Particle Number Diluter Featuring Flow Monitoring. *MDPI Proceedings* 2018, 2, 981.