ABSTRACT: Particle number exhaust emissions from diesel – and recently – from gasoline direct injection engines have already been regulated for particle sizes larger than 23 nm. However, interests have been extended to different applications and also to particles smaller than 23 nm. The UNECE Particle Measurement Programme (PMP) group is currently evaluating the feasibility to measure the sub-23 nm particle emissions by modifying the existing methodology. This paper focuses on the associated challenges of particle number measurement instruments in terms of sampling and diluting the emissions as well as of counting the sub-23 nm particles.

KEY WORDS: Environment, Emissions, Solid Particle Number, Sub-23 nm (D2)
SPN. In parallel, well-defined calibration procedures of the instruments should ensure repeatable results to be insensitive to the calibration facility and other factors. All these challenges are discussed in this paper.

2. SPN MEASUREMENT METHODOLOGY

2.1. Requirements for Counting > 23 nm SPN Emission

2.1.1. Laboratory Testing

The sampling, dilution, and measurement of SPN emission of light-duty vehicles and heavy-duty engines are prescribed according to United Nations Economic Commissions for Europe (UNECE) Regulation 83 [3] and Regulation 49 [12], respectively. The sampling is implemented by CVS system where the whole exhaust is mixed and diluted with filtered ambient air. A Particle Transfer System (PTS), which consists of a sampling probe and of a transfer tube in internal diameter of ≥ 8 mm, shall be designed as sample flow in it has a Reynolds number of < 1700 and a residence time of ≤ 3 s.

The diluted sample gas is introduced into a Volatile Particle Remover (VPR) system. The scope of the VPR is to dilute and heat the sample gas in order to remove volatile particles and to reduce its particle concentration to a lower range than the upper limit of a single count mode of a Particle Number Counter (PNC). Thus, it allows only the solid particles to reach the PNC. The VPR consists of a two-stage dilution system and of an Evaporation Tube (ET) between them. The Particle Number Dilution 1 (PND1) shall heat the sample gas at temperature of ≥ 150 °C and ≤ 400 °C, and dilute it by more than 10 times. Temperature of the ET shall be controlled in a range of 300 °C to 400 °C and higher than the PND1 temperature. The (recommended) dilution range of the Particle Number Dilution 2 (PND2) shall be between 10 and 15. It should ensure the particle concentration after the dilution is in a range of the single count mode and temperature of the sample gas at the PNC inlet is < 35 °C.

The VPR should achieve that ratios of Particle Concentration Reduction Factors (PCRFs) of particles in electrical mobility diameter of 30 nm and 50 nm to those of 100 nm are from 0.95 to 1.3 and from 0.95 to 1.2, respectively. It should also attain volatile particle removal efficiency of more than 99 % for tetracosane (CH3(CH2)38CH3) particles in diameter of 30 nm under the condition of the inlet concentration of more than 10,000 p/cm3.

The PNC shall have a linear response and counting accuracy of ± 10 % up to the upper threshold of the PNC single count mode against a traceable standard. Counting efficiencies of particles in electrical mobility diameter of 23 ± 1 nm and 41 ± 1 nm are 50 ± 12 % and > 90 %, respectively.

2.1.2. On-road Testing

A particle emission performance under RDE conditions causes additional challenges for measurement instruments due to the following reasons; (1) direct exhaust sampling, (2) extended operating conditions of engines and Emission Control Systems (ECSs), (3) harsh operating conditions (vibrations, accelerations, and inclinations), and (4) wider environmental conditions (temperature of -7 to +35 °C and altitude of up to 1,300 m). Furthermore, their power consumption must enable their on-site operation for up to 3 hours. Therefore, regulatory authorities admitted a wide range of their measurement principles. Instead of explicitly defining their detailed operating characteristics, overall efficiency criteria (combining particle losses and detection efficiencies) was defined. Consequently, none of commercialized solutions employs UNECE R83 / R49 compliant sensors but rather either advanced diffusion chargers or split-flow / handheld PNCs. The European Commission is currently investigating procedures for quantifications of the measurement accuracy under RDE conditions (altitude and temperature changes, vibrations, etc.)

Requirements for SPN measurements by PEMS are mainly based on the UNECE R83 / R49. The main differences are as follows; (1) sampling is conducted by installing a PEMS at a vehicle’s exhaust tailpipe, (2) a PTS is heated at > 100 °C, (3) alternative technologies to a PNC can be adopted for a SPN measurement, (4) the whole SPN measurement instrument including a PTS shall meet following counting efficiency requirements compared to a PNC; 0.2 - 0.6 at 23 nm, 0.3 - 1.2 at 30 nm, 0.6 - 1.3 at 50 nm, 0.7 - 1.3 at 70 nm and 100 nm, and 0.3 - 0.2 at 200 nm, (5) linearity requirements shall be attained in comparison with a PNC or an Electrometer or a UNECE R83 compliant SPN measurement system [7].

2.2. Sub-23 nm SPN Requirements and Their Activities

2.2.1. Aircraft Gas Turbine Engine Requirements

The aviation community has already implemented measurements of SPN emission in diameter of > 10 nm for certification of gas turbine engines of aircrafts [13,14]. The main differences compared to automotive SPN measurement requirements are as following; (1) a PNC shall have counting efficiencies of > 50 % and > 90 % for particles in electrical mobility diameter of 10 nm and 15 nm, respectively, (2) a VPR shall be calibrated by dilution factors instead of PCRFs, (3) particle losses in a sampling and measurement system shall be calculated based on estimation of mean particle size distribution.
This section describes challenges for SPN measurement instruments in terms of a sampling, dilution, and removal of volatile particles as well as of a count of sub-23 nm particles.

3.1. Sampling

The sampling of the sub-23 nm particles can be challenging as different sampling methods influence the final measurement results.

3.1.1. CVS Sampling

At a CVS, hot exhaust gas is mixed with colder dilution air. Condensation / absorption of hydrocarbons / sulfates / water take place onto existing “accumulation mode” particles. Homogeneous nucleation of unburned fuel / oil forms “nucleation mode” particles. The particle size distribution changes as the nucleation mode creates liquid particles in around 5 - 30 nm size which dominate particle number concentration [19]. Thus, tri-modal particle size distribution is usually observed at the end of the CVS tunnel. It consists of the nucleation mode (volatile nanoparticles), the accumulation mode (carbonaceous agglomerates with condensed / absorbed hydrocarbons), and the coarse mode (re-entrained deposited particles or wear materials from engines / ECSs [20]).

SPN of the nucleation mode particles highly depends on dilution temperature and dilution ratio [21]. Thus, the UNECE R83 / R49 regulations require to exclude the nucleation mode by heating up diluted sample gas in the VPR at temperature of 300 - 400 °C so that the volatile particles can evaporate for the measurement of solid particle emission. In addition, the PNC is calibrated as particles in diameter of < 23 nm can be excluded (counting efficiency at 23 nm is 50 %). In regard to the sampling and measurements of the sub-23 nm particles, researchers suggest the usage of the CS inside the VPR system in order to remove adequately the nucleation mode particles [22, 23, 24].

A PTS may influence the sub-23 nm particle sampling through the CVS tunnel. The PTS is not currently taken into consideration for the calibration in terms of particle losses. The UNECE R83 / R49 regulations define flow conditions in the PTS in respect of Reynolds number and residence time to ensure the minimum particle losses. They give freedom to manufacturers to design the PTS outside the proposed specifications if an equivalent particle penetration at 30 nm is demonstrated. However, diffusional particle losses significantly increase for the particles in diameter of below 30 nm. Giechaskiel et al. [25], for example, estimated that a 1 m line with a flow rate of 5 l/min caused approximately 5 % loss of 10 nm particles, while for 50 nm particles the loss due to the diffusion was < 1 %. The
potential future implementation of the sub-23 nm measurement methodology may need to take into account such a particle loss at the PTS or at least to redefine the existing requirements for it.

From a viewpoint of the loss at the PTS, it is recommended that the PTS should be designed so that the particle loss there can be minimized. Fig. 1 depicts two different PTS and SPN measurement system designs. The N°1 design minimizes the particle losses at the PTS by installing the PND1 as close as possible to the CVS tunnel. A compact design of the PND1 would be necessary for its installation to the CVS system elevated from the ground. The PND1 and a block of the PND2 / ET / Condensation Particle Counter (CPC) can be calibrated in terms of the PCRFs as the whole unit. Thus, the particle losses are accounted in the final result of the SPN measurements. On the other hand, the N°2 design enables an easy connection between block of the PND1 / PND2 / ET / CPC and CVS tunnel via long and flexible PTS. The length of the PTS is required to reach the block especially when the CVS tunnel is installed at an elevated level. However, it is considered that the particle losses would be higher at the PTS in the case of especially sub-23 nm SPN measurements. It does not take into account the PCRF as the whole unit despite the fact that the PTS of the N°2 design fulfills the current UNECE R83 / R49 requirements.

3.2. Volatile Particle Remover

Table 1 presents technologies that are currently used or might be used for diluting and for removing the volatile particles from vehicle exhaust aerosol. For measuring the sub-23 nm SPN emission, appropriate technologies of primary / secondary dilutions and of volatile particle removers should be chosen to ensure an optimum performance without sacrificing measurement accuracy and stability during their operation.

| Diluter                  | Volatile Particle Remover         |
|--------------------------|-----------------------------------|
| Rotating Disk Diluter (RDD) [32] | Evaporation Tube (ET) [33]        |
| Porous Tube Diluter (PTD) [34]        | Catalytic stripper (CS) [23]      |
| Ejector Diluter (ED) [35]            | Thermodenuder (TD) [36]           |
| Continuous Diluter MFC based (CD-MFC) [37] |                                  |

3.2.1. Particle Penetration

Particles are principally lost during their transportation inside the SPN instrument mainly due to their diffusion. The smaller the particles are, the larger their diffusion coefficient is. Thus, penetration of the ED and the PTD is higher for the smaller particles [38, 39] as the design of such diluters is very simple and minimizes the particle losses. The RDD and the CD-MFC

---

Copyright © 2019 Society of Automotive Engineers of Japan, Inc. All rights reserved

208
exhibit lower penetration but the final particle losses can also depend on the CS design incorporated in the VPR [24].

Sub-23 nm SPN instruments shall comply with the PMP draft specification at first. The ratio of PCRF(15nm) / PCRF(100nm) can be less than 2 with the appropriate VPR design and the selection of individual components (PND1, VPR, and PND2). However, the calibration of the VPR with solid particles in diameter of 15 nm is challenging. The requirement of the minimum concentration of 5000 p/cm³ of monodisperse aerosol for the upstream is difficult to be achieved by aerosol particle generators. Additionally, the volatile particles in such small size exist especially for combustion produced aerosol. Therefore, it is recommended that the calibration aerosol needs its pre-treatment to ensure stable properties before entering the VPR. The VPR calibration procedures for the sub-23 nm SPN emission measurements might be re-defined for the equivalent PCRF determination irrespective of the calibration laboratories [39].

3.2.2. Volatile Removal Efficiency

All commercial SPN measurement instruments currently equip the ET to evaporate the volatile particles. The regulatory requirement (tetracontane) was calculated as it can be easily achieved when the ET is heated at wall temperature of > 200 °C [33]. However, it was found that the ET was incapable of removing different species (e.g. Sulfuric acid and Ammonium sulfate) and high concentration particles even it was heated at 400 °C [24]. Therefore, researchers suggested the usage of the combination of the ET and the CS to perform both evaporation and oxidation for the sub-23 nm SPN measurements. In addition, it is recommended that the CS should incorporate a sulfur storage characteristic to avoid the volatile particle formation downstream of the CS due to sulfate species in the exhaust gas [23]. In regard to the sampling of the raw exhaust gas where the concentration of the volatile species is high (e.g. during DPF regeneration), the usage of the CS with the sulfur storage characteristics is inevitable for the sub-23 nm SPN measurements [40].

The TD can remove the volatile particles in the exhaust gas by its first heated session to evaporate them and by its second unheated session to absorb their vaporized materials on active carbon where their vapor pressure reduces [36]. The TD is not in general recommended for the SPN instrumentations according to the PMP group as it may exhibit relatively large particle losses and depend on chemical composition of the exhaust aerosol [41].

3.3. Particle Number Counter

Cut-off size of a PNC is defined as a function of particle diameter so that it can have a counting efficiency of 50% (D50%). For a full-flow PNC, a cut-off curve of the PNC is usually adjusted by temperature difference (ΔT) of working fluid between condenser and saturator. The ΔT defines a supersaturation ratio. It determines a growth rate of particles, which coincides the counting efficiency of the PNC [42]. In the case of the full-flow PNC with the working fluid of butanol, the D50% at 23 nm is achieved when the ΔT is around 7.5 °C. However, an aerosol material used for the calibration influences the D50% as well [43]. Thus, the abovementioned value is valid for only the PNC calibrated with emery oil aerosol which is the most commonly used for the calibration of the PNC in the automotive field.

The ΔT can increase if an operator wants to reduce the D50% so that smaller particles can grow in the condenser and can be detected by the PNC. However, only the adjustment of the temperature is not enough to reach the adequate D50% at sub-23 nm for an available commercial PNC because it can lead its nonlinear response especially at high concentration of the particles [44]. The combination of the ΔT adjustment and hardware / software modifications is necessary to achieve the D50% at sub-23 nm.

4. EXPERIMENTAL INVESTIGATION OF SUB-23 NM SPN VEHICLE EMISSION

This session describes SPN emission results of a G-DI vehicle over WLTC testing. Fig. 2 shows the experimental setup. The tests were conducted at a vehicle test bench with a 1.8 L G-DI vehicle. Two AVL Particle Counters (APCs), which adopt the RDD for the PND1 and the PTD for the PND2 [32] as well as an AVL CPC for the PNC, were used and each simultaneously measured the SPN from both Engine-out (EO) and Tailpipe (TP), respectively. The both APCs were modified to measure both sub-23 nm and original SPN emissions by equipping two PNCs, one for > 10 nm and the other for > 23 nm (original), downstream of the VPRs in parallel. The CSs were also installed in the VPRs [23]. The vehicle was tested under 3 different configurations of ECSs; (1) Three Way Catalyst (TWC) (default configuration), (2) TWC + GPF, (3) TWC + 4 Way Catalyst (4WC, which is a catalyzed GPF). Note that the substrate GPF characteristics were different from each other for the configuration 2 and 3.

A bar chart in Fig. 3 shows differences of the SPN emissions normalized to EO SPN > 23 nm among the three ECS configurations. In the case of the TWC, the SPN > 23 nm emission at the TP was reduced by 29% even though the GPF was not equipped. It can be attributed to coagulation and
deposition of the particles while they were transported from the EO to the TP sampling locations. When it comes to the SPN > 10 nm, the corresponding reduction was 47 % and this relatively higher reduction can be caused by higher diffusional losses of the small particles. The configurations of the TWC + GPF and the TWC + 4WC exhibited higher SPN reductions of both SPN > 23 nm and SPN > 10 nm. The former can be a moderate approach to comply with the SPN emission limit over the WLTC (first GPF generation), whereas the latter could potentially be a solution for RDE requirements in an efficient way.

Fig. 4 illustrates percentages of the particles smaller than 23 nm estimated by differences between SPN > 10 nm and SPN > 23 nm ((SPN10 - SPN23) / SPN23). The sub-23 nm fraction at the EO for the TWC was 64 %, while that at the TP was 24 %. This can be resulted from high loss of the smaller particles. For the TWC + GPF, the sub-23 nm fraction was only 8 % and it is considered that the GPF captured the smaller particles. It is in good agreement with the case of diesel emission with DPFs [10]. In the case of the TWC + 4WC, the sub-23 nm fraction at the TP was almost identical to the case of the TWC. However, the absolute value of the SPN emissions was far below the limit (not shown here) and it is not comparable to the TWC case. The 4WC already exhibited high enough filtration efficiency.

5. CONCLUSION

Current technologies of SPN measurements have been reviewed focusing on sampling, diluting, and removing volatile particles as well as on counting SPN. Challenges for a sub-23 nm measurement have also been addressed and individual components of a PTS, a PND1, a VPR and a PND2 should ensure the following points:

- Capability of the PTS to minimize particle losses when sampling exhaust gas.
- A technology for the PND1 to meet penetration requirements (especially for sub-23 nm) without deterioration of its stability and robustness under the sampling conditions (pressure differences / fluctuations, water condensation, coarse mode particles, and high concentrations).
- A technology of the VPR to efficiently remove volatile species (i.e. ET + CS).
- A technology of the PND2 to reduce particle concentration and to minimize particle losses.
- Enhancement of the PNC performances to count sub-23 nm particles adequately in combination with its hardware and software modifications.
- Well-defined VPR and PNC calibration procedures which are also traceable to international standards such as ISO 17025.

Experimental results of SPN measurements from a G-DI vehicle indicated that sub-23 nm fractions before and after TWC were 64-78 % and 24 %, respectively. They also implied that a
GPF and a 4WC efficiently reduced the SPN emissions irrespective of their particle size.

ACKNOWLEDGEMENT

Part of the work reported here is part of the Upgrade project which received funding from the European Union’s Horizon 2020 research and innovation program under grant agreement No 724036.

This paper is written based on a proceeding presented at JSAE 2018 Annual Congress.

ABBREVIATIONS

4WC 4 Way Catalyst
APC AVL Particle Counter
CD-MFC Continuous Diluter MFC based
CPC Condensation Particle Counter
CS Catalytic Stripper
CVS Constant Volume Sampling
DPF Diesel Particulate Filter
ECS Emission Control System
ED Ejector Diluter
EO Engine-out
ET Evaporation Tube
EU European Union
G-DI Gasoline Direct Injection
GPF Gasoline Particulate Filter
NEDC New European Driving Cycle
PCRF Particulate Concentration Reduction Factor
PEMS Portable Emission Measurement Systems
PMP Particle Measurement Programme
PNC Particle Number Counter
PND Particle Number Dilution
PTD Porous Tube Diluter
PTS Particle Transfer System
RDD Rotating Disk Diluter
RDE Real Driving Emissions
SPN Solid Particle Number
TD Thermodenuder
TP Tailpipe
TWC Three Way Catalyst
UNECE United Nations Economic Commissions for Europe
VPR Volatile Particle Remover
WLTC Worldwide Harmonized Light Duty Test Cycle
ΔT Temperature Difference

REFERENCES

(1) Giechaskiel B. et al.: Measurement of Automotive Nonvolatile Particle Number Emissions within the European Legislative Framework: A Review, Aerosol Science and Technology, 46, p.719-749 (2012).
(2) Commissions Delegated Regulation (EU) 2017/654 of 19 December 2016.
(3) Regulation No. 83, Revision 5, “Uniform provisions concerning the approval of vehicles with regard to the emission of pollutants according to engine fuel requirements” United Nations, 02/2015.
(4) Demuynck J. et al.: Recommendations for the new WLTP cycle based on an analysis of vehicle emission measurements on NEDC and CADC, Energy Policy, 49, p.234-242 (2012).
(5) Weiss M. et al.: On-Road Emissions of Light-Duty Vehicles in Europe, Environ. Sci. Technol. 45, 19, p.8575-8581, (2011).
(6) Tutuianu M. et al.: Development of the World-wide harmonized Light duty Test Cycle (WLTC) and a possible pathway for its introduction in the European legislation, Transportation Research Part D: Transport and Environment, 40, p.61-75, (2015).
(7) Commissions Regulation (EU) 2017/1154 of 7 June 2017.
(8) Yang J. et al.: Single Wall Diesel Particulate Filter (DPF) Filtration Efficiency Studies Using Laboratory Generated Particles, Chem. Eng. Sci., 64, p.1625-1634, (2009).
(9) Oberdörster G. et al.: Translocation of Inhaled Ultrafine Particles to the Brain, Inhal Toxicol., 16(6-7), p.437-45, (2004).
(10) Giechaskiel B. et al.: Investigation of vehicle exhaust sub-23 nm particle emissions, Aerosol Science and Technology, 51(5), p.626-641, (2017).
(11) United Nations, 42th UNECE IWG PMP MEETING, “Exhaust emissions”, Joint Research Centre.
(12) Regulation No. 49, Revision 6, “Uniform provisions concerning the measures to be taken against the emissions of gaseous and particulate pollutants from compression-ignition engines and positive ignition engines for use in vehicles” United Nations, 03/2013.
(13) SAE Aerospace Information Report – AIR6241: Procedure for the Continuous Sampling and Measurement of Non-Volatile Particle Emissions from Aircraft Turbine Engines, (2013).
(14) Lobo P. et al.: Measurement of Aircraft Engine Non-Volatile PM emissions: results of the aviation-particle regulatory instrumentation demonstration experiment (A-PRIDE) 4 campaign, Aerosol Science and Technology, 49(7), p.472-484, (2015).
(15) United Nations, 46th UNECE IWG PMP Meeting, “PMP progress report to GRPE.”
(16) European Commission, Horizon 2020, DownToTen.
(17) European Commission, Horizon 2020, PEMs4Nano.
(18) European Commission, Horizon 2020, SUREAL-23.
(19) Kittelson D.: Engines and Nanoparticles: A Review, Journal of Aerosol Science, 29(5), p.575-588, (1998).
(20) Kittelson D., Johnson J.: Variability in Particle Emission Measurements in the Heavy Duty Transient Test, SAE Technical Paper 910738, (1991).
(21) Mathis U. et al.: Sampling Conditions for the Measurement of Nucleation Mode Particles in the Exhaust of a Diesel Vehicle, Aerosol Science and Technology 38, p.1149-1160, (2004).
(22) Abdul-Khalek I., Kittelson D.: Real Time Measurement of Volatile and Solid Exhaust Particles Using a Catalytic Stripper, SAE Technical Paper 950236, (1995).
(23) Amanatidis S., et al.: Evaluation of an oxidation catalyst (“catalytic stripper”) in eliminating volatile material from combustion aerosol, Journal of Aerosol Science 57, p.144-155, (2013).
(24) Otsuki, Y. et al.: A Solid Particle Number Measurement System Including Nanoparticles Smaller than 23 Nanometers, SAE Technical Paper 2014-01-1604, (2014).
(25) Giechaskiel B. et al.: Sampling of Non-Volatile Vehicle Exhaust Particles: A Simplified Guide, SAE Int. J. Engines 5(2), p.:379-399, (2012).
(26) Cavina N. et al.: Benchmark Comparison of Commercially Available Systems for Particle Number Measurement, SAE Technical Paper 2013-24-0182, (2013).
(27) Mamakos A., et al.: A Robust Solution to On-Board Particle Number Measurements, JSAE Paper Number 20165214, (2016).
(28) Stratmann F. et al.: Thermophoretal and diffusional particle transport in cooled laminar tube flow, Journal of Aerosol Science 25(7), p.1305-1319, (1994).
(29) Giechaskiel, B. et al.: Comparison of Particle Number Measurements from the Full Dilution Tunnel, the Tailpipe and Two Partial Flow Systems, SAE Technical Paper 2010-01-1299, (2010).
(30) Isella L. et al.: Diesel-exhaust aerosol dynamics from the tailpipe to the dilution tunnel, Journal of Aerosol Science 39(9), p.737-758, (2008).
(31) Ntziachristos L. et al.: Comparative Assessment of Two Different Sampling Systems for Particle Emission Type-Approval Measurements, SAE Technical Paper 2005-01-0198, (2005).
(32) Giechaskiel B., et al.: Calibration and accuracy of a particle number measurement system, Meas. Sci. Technol. 21(4), 045102 (13pp), (2010).
(33) Giechaskiel B., Drossinos Y.: Theoretical Investigation of Volatile Removal Efficiency of Particle Number Measurement Systems, SAE Int. J. Engines 3(1), p.1140-1151, (2010).
(34) Mikkanen P. et al.: Sampling Method for Particle Measurements of Vehicle Exhaust, SAE Technical Paper 2001-01-0219, (2001).
(35) Giechaskiel B. et al.: Calibration and modelling of ejector dilutors for automotive exhaust sampling, Meas. Sci. Technol. 15, p.2199-2206, (2004).
(36) Huffman A. et al.: Development and Characterization of a Fast-Stepping/Scanning Thermodenuer for Chemically-Resolved Aerosol Volatility Measurements, Aerosol Science and Technology 42(5), p.395-407, (2008).
(37) Wei Q. et al.: Real-Time Measuring System for Engine Exhaust Solid Particle Number Emission - Design and Performance, SAE Technical Paper 2006-01-0864, (2006).
(38) Giechaskiel B. et al.: Calibration and Validation of Various Commercial Particle Number Measurement Systems, SAE Int. J. Fuels Lubr. 2(1), p.512-530, (2009).
(39) Mamakos A. et al.: Particle Measurement Programme. Volatile Particle Remover Calibration Round Robin. Report EUR 25512 EN, (2012).
(40) Giechaskiel B. and Martini, G.: Engine Exhaust Solid Sub-23 nm Particles: II. Feasibility Study for Particle Number Measurement Systems, SAE Int. J. Fuels Lubr. 7(3), p.935-949, (2014).
(41) Report of the GRPE Particle Measurement Programme (PMP) Government Sponsored Work Programmes, (2003).
(42) McDermott W. et al.: Counting Efficiency of an Improved 30-Å Condensation Nucleus Counter, Aerosol Science and Technology 14(2), p.278-287, (1991).
(43) Giechaskiel B. et al.: Calibration of Condensation Particle Counters for Legislated Vehicle Number Emission Measurements, Aerosol Science and Technology 43(12), p.1164-1173, (2009).
(44) Giechaskiel B., Bergmann A.: On-Site Checks of the Particle Number Measurement Systems with Polydisperse Aerosol, SAE Int. J. Engines 5(2), p.649-662, (2012).