Real Driving Emissions (RDE)

Particle Number (PN) Portable Measurement Systems (PEMS) calibration

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Contents

Foreword

Regulation (EU) 2016/427 (first regulatory package of the Real-Driving Emissions regulation, RDE1) introduced on-road testing with Portable Emissions Measurement Systems (PEMS) to complement the laboratory Type I test for the type approval of light-duty vehicles in the European Union (EU). Subsequently, Regulation (EU) 2016/646 (RDE2) introduced Real Driving Emissions (RDE) conformity factors for nitrogen oxides (NOx) emissions in two steps. Both regulations were consolidated in the World Harmonized Light Duty test Procedure (WLTP) Regulation (EU) 2017/1151 and further developed by Regulation (EU) 2017/1154 (RDE3), which also introduced an RDE conformity factor for the on-road test of ultrafine particle emissions.

The technical specifications of the Particle Number (PN) Portable Emission Measurement System (PEMS) have major differences compared to the technical specification of the regulated systems from the dilution tunnel. This has created confusion regarding the calibration procedures of the portable.

Objective of this report is to summarize the calibration procedures of the PN-PEMS and give examples and possible ways.

Acknowledgements

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Authors

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Abstract

The PN-PEMS is considered a "black box" where efficiency tests and linearity have to be checked with thermally stable soot like aerosol. The efficiency is checked with monodisperse aerosol. The most straight forward way is to check the efficiency of the complete PN-PEMS but checking the thermal pre-conditioning unit and the particle detector of the PN-PEMS separately is also permissible. In the second case the two results have to be combined in one penetration efficiency. For the linearity check usually polydisperse aerosol is used in order to reach high concentration levels.

1   Introduction

The *Particle Number (PN) Portable Emission Measurement System (PEMS)* consists of a *PN analyser* and optionally a *sampling line*. The PN analyser typically consists of a dilution and thermal *pre-conditioning unit* and a *particle detector*. The particle detector is usually a *Condensation Particle Counter (CPC)* or a *Diffusion Charger (DC)*. The regulation includes some obligatory design characteristics (e.g. temperatures, residence times), but focuses mainly on performance characteristics (efficiency in function of size, linearity in function of concentration, volatile removal efficiency).

The following chapters will give in detail the regulation (**Chapter 2**) and the calibration procedures to prove the performance requirements (**Chapter 3** for efficiency calibration, **Chapter 4** for linearity, **Chapter 5** for the volatile removal efficiency).

The design characteristics of the systems and/or the validation requirements in a chassis dynamometer are out of the scope of this report.

2 Regulation

According to regulation 2017/1154:

2.1 General

The PN analyser shall be connected to the sampling point via a sampling probe which extracts a sample from the centreline of the tailpipe tube. If particles are not diluted at the tailpipe, the sampling line shall be heated to a minimum temperature of 373 K (100 °C) until the point of first dilution of the PN analyser or the particle detector of the analyser. The residence time in the sampling line shall be less than 3 s.

All parts in contact with the sampled exhaust gas shall be always kept at a temperature that avoids condensation of any compound in the device. This can be achieved, e.g. by heating at a higher temperature and diluting the sample or oxidizing the (semi)volatile species.

The PN analyser shall include a heated section at wall temperature ≥ 573 K. The unit shall control the heated stages to constant nominal operating temperatures, within a tolerance of ± 10 K and provide an indication of whether or not heated stages are at their correct operating temperatures. Lower temperatures are acceptable as long as the volatile particle removal efficiency fulfils the specifications of **Section 2.4**.
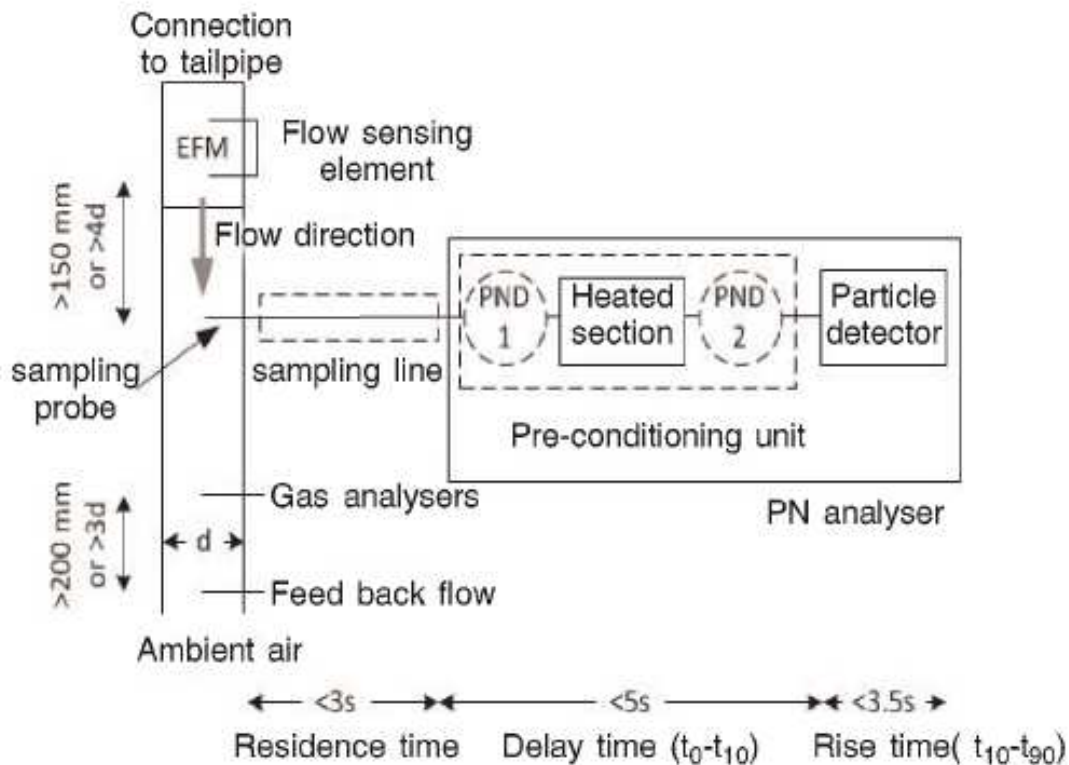
Figure 1.1: Example of a PN analyser setup: Dotted lines depict optional parts. EFM = Exhaust mass Flow Meter, d = inner diameter, PND = Particle Number Diluter.

Pressure, temperature and other sensors shall monitor the proper operation of the instrument during operation and trigger a warning or message in case of malfunction.

The delay time of the PN analyser shall be ≤ 5 s.

The PN analyser (and/or particle detector) shall have a rise time of ≤ 3,5 s.

Particle concentration measurements shall be reported normalised to 273 K and 101,3 kPa. If necessary, the pressure and/or temperature at the inlet of the detector shall be measured and reported for the purposes of normalizing the particle concentration.

PN systems that comply with the calibration requirements of the UNECE Regulations 83 or 49 or GTR 15 automatically comply with the calibration requirements for PN-PEMS.

Zero check: The zero level of the analyser shall be recorded by sampling HEPA filtered ambient air. The signal shall be recorded at a constant frequency of at least 1,0 Hz over a period of 2 min and averaged. The final concentration shall be within the manufacturer's specifications, but shall not exceed 5000 p/cm^3.

Span check shall be conducted according to the manufacturer.

2.2 Efficiency requirements

The complete PN analyser system including the sampling line shall fulfil the efficiency requirements of **Table 2.1**.

Table 2.1: PN analyser (including the sample line) system efficiency requirements.

d_p [nm]	Sub-23	23	30	50	70	100	200
E(d_p) PN analyser	To be determined	0,2 – 0,6	0,3 – 1,2	0,6 – 1,3	0,7 – 1,3	0,7 – 1,3	0,5 – 2,0

Efficiency E(dp) is defined as the ratio in the readings of the PN analyser system to a reference Condensation Particle Counter (CPC)'s ($d_{50\%}$ = 10 nm or lower, checked for linearity and calibrated with an electrometer) or an Electrometer's number concentration measuring in parallel monodisperse aerosol of mobility diameter dp and normalized at the same temperature and pressure conditions.

The material should be thermally stable soot-like (e.g. spark discharged graphite or diffusion flame soot with thermal pre-treatment). If the efficiency curve is measured with a different aerosol (e.g. NaCl), the correlation to the soot-like curve must be provided as a chart, which compares the efficiencies obtained using both test aerosols. The differences in the counting efficiencies have to be taken into account by adjusting the measured efficiencies based on the provided chart to give soot-like aerosol efficiencies. The correction for multiply charged particles should be applied and documented but shall not exceed 10%. These efficiencies refer to the PN analysers with the sampling line. The PN analyser can also be calibrated in parts (i.e. the pre-conditioning unit separately from the particle detector) as long as it is proven that PN analyser and the sampling line together fulfil the requirements of **Table 2.1**. The measured signal from the detector shall be > 2 times the limit of detection (here defined as the zero level plus 3 standard deviations).

2.3 Linearity requirements

Linearity requirements of PN analysers shall be verified, whenever damage is observed, as required by internal audit procedures or by the instrument manufacturer but no longer than one year before the actual test.

The PN analyser including the sampling line shall fulfil the linearity requirements of **Table 2.2** using monodisperse or polydisperse soot-like particles. The particle size (mobility diameter or count median diameter) should be larger than 45 nm. The reference instrument shall be an Electrometer or a Condensation Particle Counter (CPC) with d_{50}=10 nm or lower, verified for linearity. Alternatively, a particle number system compliant with UNECE Regulation 83 or 49 or GTR 15.

Table 2.2: Linearity requirements of measurement parameters and systems.

'Measurement parameter/instrument	$\lvert x_{min} \times (a_1 - 1) + a_0 \rvert$	Slope a_1	Standard error SEE	Coefficient of determination r^2
Fuel flow rate ([1])	≤ 1 % max	0,98 – 1,02	≤ 2 %	≥ 0,990
Air flow rate ([1])	≤ 1 % max	0,98 – 1,02	≤ 2 %	≥ 0,990
Exhaust mass flow rate	≤ 2 % max	0,97 – 1,03	≤ 3 %	≥ 0,990
Gas analysers	≤ 0,5 % max	0,99 – 1,01	≤ 1 %	≥ 0,998
Torque ([2])	≤ 1 % max	0,98 – 1,02	≤ 2 %	≥ 0,990
PN analysers ([3])	≤ 5 % max	0,85 – 1,15 ([4])	≤ 10 %	≥ 0,950

([1]) optional to determine exhaust mass flow
([2]) optional parameter
([3]) The linearity check shall be verified with soot-like particles, as these are defined in point 6.2
([4]) To be updated based on error propagation and traceability charts.';

In addition the differences of the PN analyser from the reference instrument at all points checked (except the zero point) shall be within 15% of their mean value. At least 5 points equally distributed (plus the zero) shall be checked. The maximum checked concentration shall be the maximum allowed concentration of the PN analyser.

If the PN analyser is calibrated in parts, then the linearity can be checked only for the PN detector, but the efficiencies of the rest parts and the sampling line have to be considered in the slope calculation.

2.4 Volatile removal efficiency

The system shall achieve >99% removal of ≥30 nm tetracontane ($CH_3(CH_2)_{38}CH_3$) particles with an inlet concentration of ≥10.000 particles per cubic-centimetre at the minimum dilution.

The system shall also achieve a >99% removal efficiency of polydisperse alcane (decane or higher) or emery oil with count median diameter >50 nm and mass >1 mg/m^3.

The volatile removal efficiency with tetracontane and/or polydisperse alcane or oil have to be proven only once for the instrument family. The instrument manufacturer though has to provide the maintenance or replacement interval that ensures that the removal efficiency does not drop below the technical requirements. If such information is not provided, the volatile removal efficiency has to be checked yearly for each instrument.

2.5 Validation of PN analyzer

The comparison of the PEMS with the laboratory equipment on a chassis dynamometer is a check of the functionality of the complete PEMS once it is fully installed in the vehicle. In the context of RDE measurements, is called a "validation of PEMS" and is not meant to compare the respective measurement performance of the laboratory and the PEMS test principles. Such a validation test only ensures that the PEMS is correctly installed and functioning when its emissions over a WLTC are found to be within a reasonable range around the ones given by the CVS.

It is recommended to validate the installed PEMS once for each PEMS-vehicle combination either before the test or, alternatively, after the completion of an on-road test. The PEMS installation should be kept unchanged in the time period between the on-road test and the validation. The permissible tolerances of this validation are given in the RDE Regulation. The PEMS validation results should fulfil the requirements given in **Table 2.3**. If any permissible tolerance is not met, corrective action shall be taken and the PEMS validation shall be repeated.

Table 2.3: Permissible tolerance.

Parameter [Unit]	Permissible absolute tolerance
Distance [km] (¹)	250 m of the laboratory reference
THC (²) [mg/km]	15 mg/km or 15 % of the laboratory reference, whichever is larger
CH_4 (²) [mg/km]	15 mg/km or 15 % of the laboratory reference, whichever is larger
NMHC (²) [mg/km]	20 mg/km or 20 % of the laboratory reference, whichever is larger
PN (²) [#/km]	$1 \bullet 10^{11}$ p/km or 50 % of the laboratory reference (³) whichever is larger
CO (²) [mg/km]	150 mg/km or 15 % of the laboratory reference, whichever is larger
CO_2 [g/km]	10 g/km or 10 % of the laboratory reference, whichever is larger
NO_x (²) [mg/km]	15 mg/km or 15 % of the laboratory reference, whichever is larger

(¹) only applicable if vehicle speed is determined by the ECU; to meet the permissible tolerance it is permitted to adjust the ECU vehicle speed measurements based on the outcome of the validation test
(²) parameter only mandatory if measurement required by point 2.1 of this Annex.
(³) PMP system';

3 Efficiency (monodisperse)

3.1 Setup

The efficiency characteristics of the PN-PEMS have to be checked with monodisperse aerosol. The tests can be conducted for the complete PN-PEMS or its parts separately. For PN-PEMS with many dilution settings, the efficiency requirements need to be checked for all (dilution) setting that can be used for regulatory purposes. If the PN-PEMS efficiency curves are checked for the PN-PEMS in parts, they have to be multiplied to each other to give the complete PN-PEMS efficiency curve. A typical split is thermal pre-conditioning and dilution unit, and the particle detector (sensor). However this is not necessary; there are cases where primary dilution and thermal pre-treatment are checked as one part and the secondary dilution with the particle detector as the second part. The efficiency requirements have been presented in **Section 2.2**.

The necessary instrumentation for the efficiency measurements includes (**Figure 3.1**):

- An aerosol generator assembly producing thermally stable soot-like particles at the necessary concentrations.

- A Differential Mobility Analyzer (DMA) for the extraction of particles of the regulated electrical mobility diameters.

- Bipolar charger(s) to condition the aerosol for the DMA and perhaps also for the PN-PEMS particle detector.

- A reference instrument to measure the absolute concentration of the produced monodisperse particles.

The aerosol generator assembly must ensure that the produced particles do not change size and/or shape when sampled through the PN-PEMS system. If necessary, one or more dilution stages can also be applied to bring the concentration within the desirable range (measured signal from the detector shall be >2 times the limit of detection defined as the zero level plus 3 standard deviations). These dilution stages can be either incorporated in the generator or applied externally. If the employed generators are producing non-soot-like aerosols (e.g. NaCl), the correlation to the soot-like efficiency curve must be provided, which compares the efficiencies obtained using both test aerosols. The differences in the counting efficiencies have to be taken into account by adjusting the measured efficiencies based on the provided chart to give soot-like aerosol efficiencies.

The DMA should be capable of covering at least the size range of 23 to 200 nm at its operating conditions. The sheath over sample flowrate should be at or above 5:1, preferably ≥7:1. The DMA can operate either in overpressure or in underpressure mode, provided that the operating pressure is within the specifications of the DMA manufacturer. The charge state of the polydisperse aerosol reaching the DMA column should be conditioned to minimize interference from multiple charged particles. If necessary, a bipolar charger (i.e. radioactive source, x-ray, etc.) should be employed upstream of the DMA column. The flow extracted from the DMA should be within the specifications of the DMA and (in case used) the bipolar charger. If necessary some make-up conditioned air can be introduced at the outlet of the DMA to control the extracted flow. The particles exiting the DMA will be (ideally mostly singly) charged. If this charge state interferes with the operation of the sensor (i.e. DC based instruments) the classified monodisperse aerosol should be conditioned once more with a bipolar charger.

The reference instrument against which the PN-PEMS is calibrated can be either an electrometer or a full flow CPC. If the classified monodisperse aerosol is conditioned in a bipolar charger, an electrometer cannot be used. The concentrations measured both with the reference instrument and the PN-PEMS must be reported at the same conditions (pressure and temperature). If the reference instrument does not have a 100% counting

efficiency at a given size (i.e. at 23 nm) its response should be corrected, but the correction should not be higher than 10% from the slope. Furthermore, a correction of the reference concentration for its sample flow should be applied provided that the reference instrument operates in full flow.

If dilution is employed downstream of the DMA (i.e. when make-up air is employed), care needs to be taken to ensure proper mixing before feeding the diluted monodisperse aerosol to the reference instrument and the PN-PEMS (or particle detector) under calibration. Proper mixing is typically checked by changing position of the reference instrument and the PN-PEMS. The differences should be within experimental uncertainty (typically <2%).

The efficiency E at a specific size is defined as the ratio of the response R of the PN-PEMS (or the sensor) to the concentration PN measured by the reference instrument (corrected for flow etc.).

$$E_{PN-PEMS} = \frac{R_{PN-PEMS}}{PN_{REF}}$$
3.1

The efficiency E can be checked for the whole PN-PEMS or its parts independently. In the second case the efficiencies of the parts have to be combined for the final total efficiency.

3.2 Multiply charged particles correction

The correction for multiply charged particles should be applied and documented but shall not exceed 10%.

Charging efficiencies for spherical particles can be considered (Wiedensohler 1988, Kulkarni 2011), although the soot generators produce agglomerate particles with higher charging fractions (Bau et al., 2010, Mamakos 2016). If the charging equilibrium is known, it can be applied.

The importance of the multiply charged particles is higher at bigger sizes due to the higher charging probability. To minimize the effect of multiply charged particles it is recommended to produce size distributions (upstream of the DMA) with mean size smaller that the size selected at the DMA. Tandem DMA setups can significantly reduce the fraction.

Table 3.1 gives an example of the doubly to singly charged particle fraction based on spherical particles and the estimated contribution of the doubly charged particles assuming that the concentration measured at double voltage is 30% of the concentration measured at the specific tested size (normal voltage). For details see supplemental info of Giechaskiel et al. (2009). The final applied correction depends on other parameters as well (such as the principle of operation of both the reference and tested instruments).

Table 3.1: Example of double charge fraction and contribution of doubly charged particles assuming that the concentration at the double voltage is 30% of the concentration at the tested size.

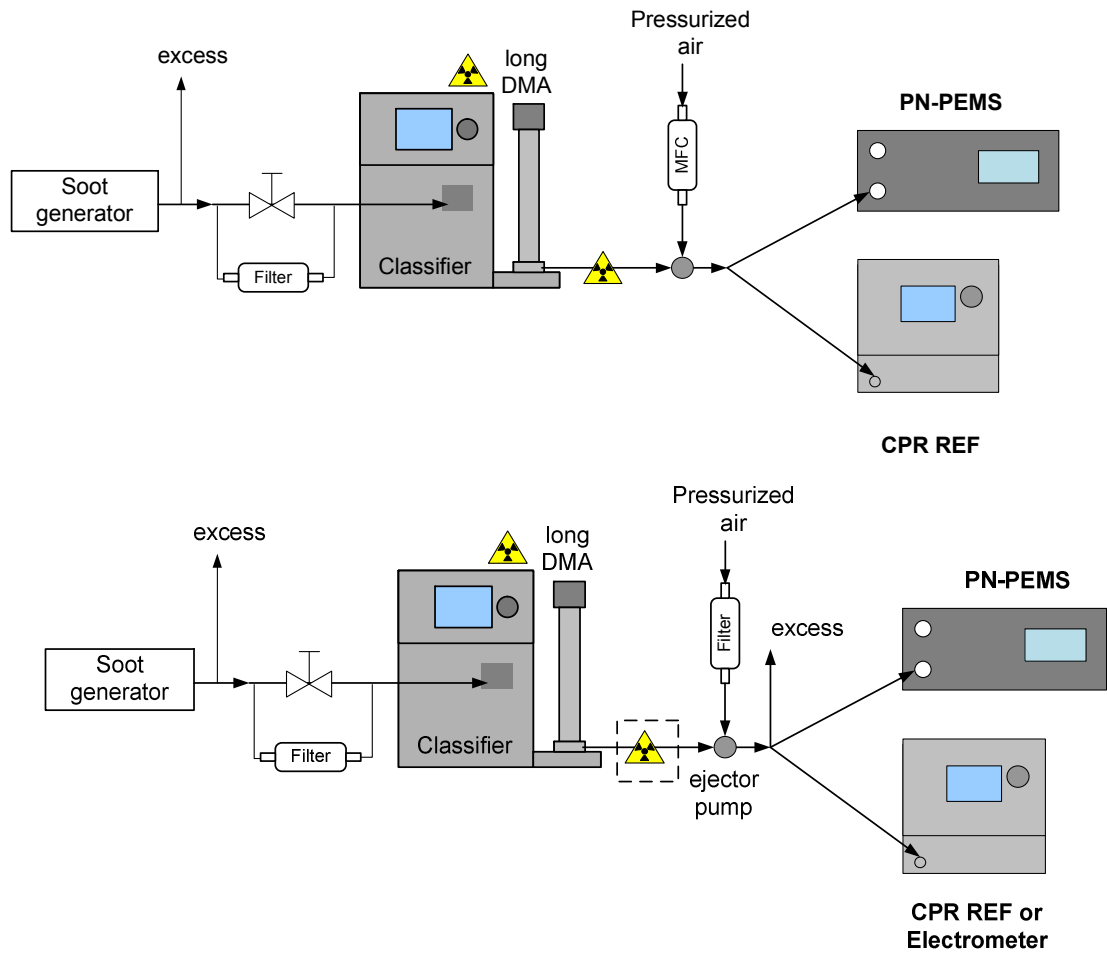| dp(1*V)	C@dp(1*V)	dp2(2*V)	C@dp2(2*V)		f1@dp2	f2@dp2	f2/f1	double charge fr.
dp1	C1	dp2	C2	C2/C1	f1	f2	f2/f1	C2/C1*f2/f1
15	10000	21	3000	30%	12%	0%	0%	**0.1%**
23	10000	33	3000	30%	17%	0%	1%	**0.4%**
30	10000	43	3000	30%	20%	1%	3%	**1.0%**
50	10000	71	3000	30%	26%	3%	11%	**3.4%**
70	10000	100	3000	30%	28%	6%	20%	**6.0%**
100	10000	143	3000	30%	28%	9%	32%	**9.7%**
200	10000	285	3000	30%	23%	14%	61%	**18.3%**

Figure 3.1: Examples of setups for the monodisperse aerosol tests. Instead of PN-PEMS only the particle detector or other parts of the PN-PEMS could be checked. The second neutralizer is necessary only when the PN-PEMS has a DC based particle detector. Instead of ejector pump, a mixing orifice with a Mass Flow Controller (MFC) can be used.

4 Linearity

There are two possibilities to check the linearity of the PN-PEMS:

- The complete PN-PEMS is checked with polydisperse aerosol.
- The particle detector is checked for linearity (monodisperse or polydisperse aerosol). In this case the efficiencies of the rest parts and the sampling line (for the specific size) have to be considered in the slope calculation.

In the regulation it is stated that the maximum checked concentration shall be the maximum allowed concentration of the PN analyser. In the first case it is straight forward. In the second case it is the maximum concentration checked for the particle detector multiplied by the maximum dilution setting (or PCRF) checked for efficiency requirements.

Although the selection of size is not strictly defined in the regulation (>45 nm), the idea behind is to select a size that gives an efficiency of 100%, as the slope needs to be within 0.85 and 1.15

Note also that the linearity result (i.e. slope) does not have to be applied to the PN-PEMS (i.e. the PN-PEMS does not have to be adjusted), as long as the requirements are fulfilled. If any adjustment takes place, the efficiency requirements (**Chapter 3**) have to be fulfilled applying this factor.

4.1 Polydisperse measurements

The equipment required for the polydisperse characterization of the PN-PEMS linearity includes (**Figure 4.1**):

- An aerosol generator assembly producing thermally stable soot-like particles at the necessary concentrations.
- A Scanning Mobility Particle Sizer (SMPS) for the measurement of the number-weighted mobility size distribution.
- Bipolar charger(s) to condition the aerosol for the SMPS and perhaps also for the PN-PEMS sensor.
- A reference instrument to measure the absolute concentration of the produced polydisperse particles.

The aerosol generator assembly must ensure that the produced particles do not change size and/or shape when sampled through the PN-PEMS system and the reference instrumentation. One or more dilution stages can be applied to adjust the concentration within the desirable range. These dilution stages can be either incorporated in the generator or applied externally. The charge state of the produced polydisperse aerosol should be conditioned to minimize interference from multiple charged particles for both the SMPS and the PN-PEMS. If necessary, one or more bipolar chargers (i.e. radioactive source, x-ray, etc.) should be employed before feeding the polydisperse aerosol to the instrumentation. Care needs to be taken, to ensure that the flow through the bipolar charger remains within the range specified by the manufacturer. Some make-up air may be necessary.

The SMPS should cover the size range of at least 15 to 200 nm. The recovered size distribution should correct the raw signal for diffusion losses and multiple charges. If the aerosol is already neutralized by a bipolar charger, there is no need for a dedicated bipolar charger upstream of the DMA column. The measured distributions shall be checked to verify that the count median diameter is above 45 nm.

The SMPS does not have to measure during the linearity checks, but it is highly recommended. However, it has to be used at the beginning and at the end of the tests, or every time the generator settings are adjusted. Adjustments might be needed for

example to account for shifts in the size distribution (e.g. due to particle coagulation at high concentrations).

The reference instrument against which the PN-PEMS (or its sensor) is checked shall be a UNECE Regulation 83 or 49 or GTR 15 compliant particle number measurement system. Calibrated CPCs checked for linearity that cover the desired concentration range are also permitted.

Care needs to be taken to ensure that the diluted sample after dilution and before splitting to the two or three different instruments is well mixed.

For PN-PEMS with DCs as particle detectors the aerosol shouldn't be too charged. Thus, for spark-discharge generators, the neutralizers are necessary. Diffusion flame soot polydisperse aerosol is considered to be on average neutral, thus no neutralizer is necessary. However, it is recommended to have one.
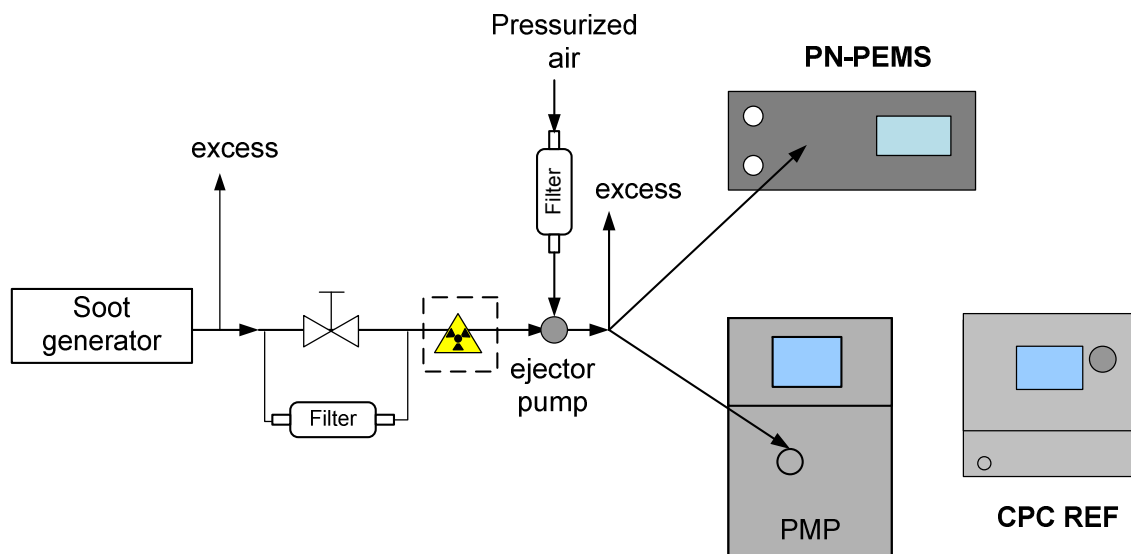

Figure 4.1: Example of setup for polydisperse linearity check.

4.2 Monodisperse measurements

When monodisperse aerosol is employed, a setup described in **Section 3.1** (**Figure 3.1**) shall be used.

The classification size shall be above 45 nm and should lead to an overall PN-PEMS efficiency of around 100%. If non-soot-like particles are used, the correlation factor to soot at the selected size shall be employed.

At the same size the concentration of the classified monodisperse aerosol shall be adjusted to cover at least five concentrations spanning from approximately the noise level of the reference instrument to the upper measurement range of the PN-PEMS. The adjustment of the concentration can be achieved by means of dilution either upstream or downstream of the DMA.

Given that the use of the DMA introduces a considerable reduction in the concentration (typically $<10^5$ p/cm^3), this approach is only suited for linearity checks of the particle detector alone.

Note that, if the PN-PEMS is calibrated in parts, then the linearity can be checked only for the PN detector, but the efficiencies of the rest parts and the sampling line have to be considered in the slope calculation.

5 Volatile removal efficiency

The volatile removal efficiency has to be checked with ≥30 nm tetracontane particles. Typically the setup of **Figure 3.1** is used with an evaporation / condensation generator.

For the polydisperse test the setup of **Figure 4.1** can be used with the appropriate generator (e.g. decane, tetracontane, emery oil).

The volatile removal efficiency can be determined with a different detector than the PN-PEMS particle detector provided that the employed detector has a lower cut-off size than the PN-PEMS particle detector.

6 Other checks

6.1 Leak check

This is obligatory. Some systems have available an automated underpressure leak check, while others a manual one. Most CPC based PN-PEMS use the HEPA filter zero check as leak check (but with much lower than 5000 p/cm^3 limit).

6.2 Zero check

The zero check of CPC-based systems is usually very close to 0 p/cm^3. The zero check of DC-based systems has to be blow 5000 p/cm^3.

7 Calibration examples

Some examples are given below. These are not the only possibilities but only two of the many possibilities for calibration.

7.1 One dilution setting and CPC based particle detector

Linearity check with soot (monodisperse or polydisperse) and a reference instrument with size ≥45 nm. In this example monodisperse aerosol with a size of 75 nm was used. A reference CPC was chosen to minimize the influence of multiply charged particles.

Table 7.1: Linearity check with monodisperse soot aerosol (size 75 nm). The differences should be within 15% of their mean value.

Reference CPC	Particle detector	Difference (±15%)
0.0	0.0	-
1227.2	1150.9	-6.2%
2825.4	2690.3	-4.8%
4777.2	4594.2	-3.8%
7135.8	6766.1	-5.2%
10469.4	9963.8	-4.8%
14714.7	13948.6	-5.2%
28637.8	27070.1	-5.5%

	$\lvert \chi_{min} \times (a_1 - 1 + a_0 \rvert$	Slope a_1	SEE	r^2
Threshold	≤5% max	0.85-1.15	≤10%	≥0.950
Measured	0.1% χ_{max}	0.95	0.12%	1.000

The slope can be applied at the internal CPC (i.e. correction 1/0.95=1.058).

Determination of an internal dilution with particle losses (usually at a size typical for vehicle exhaust, e.g. 70 nm if a reference CPC is used).

Dilution setting	Upstream	Downstream	Dilution with losses	Corr. Factor
100	14300	128	111.7	1.117

This step is not obligatory and can be done during the efficiency check by shifting the whole curve.

Max allowed concentration for this system: 111.7 x 28637.8 = 3 x 10^6 p/cm^3.

If the previous step was not conducted: 100.0 x 28637.8 = 2.8 x 10^6 p/cm^3.

Check of the complete system efficiency with a reference CPC (**Table 7.2**). The corrections for multiply charged particles were assumed 0%.

Table 7.2: Efficiency check of the complete PN-PEMS (monodisperse aerosol) for one dilution setting.

Size [nm]	Total	Limits
15	0.01	n.d.
23	0.40	0.2 – 0.6
30	0.61	0.3 – 1.2
50	0.91	0.6 – 1.3
70	0.97	0.7 – 1.3
100	0.99	0.7 – 1.3
200	1.04	0.5 – 2.0

Another example where the efficiency check of the PN-PEMS is done in two parts and the internal CPC is included in the second part (**Table 7.3**):

Table 7.3: Efficiency check of a PN-PEMS in two parts (monodisperse aerosol) for one dilution setting.

Size [nm]	Efficiency 1	Efficiency 2	Total	Limits
15	0.57	0.20	0.11	n.d.
23	0.84	0.48	0.41	0.2 – 0.6
30	0.91	0.68	0.62	0.3 – 1.2
50	1.00	0.84	0.84	0.6 – 1.3
70	1.03	1.00	1.03	0.7 – 1.3
100	1.02	1.05	1.07	0.7 – 1.3
200	1.00	1.07	1.07	0.5 – 2.0

If the PN-PEMS has a second dilution setting it has to be calibrated for the efficiency as well.

7.2 One dilution setting and DC based particle detector

The linearity is conducted for the whole system against a PMP system with soot aerosol of count median diameter of e.g. 50 nm.

Table 7.4: Linearity check with polydisperse soot aerosol (CMD 50 nm). The differences should be within 15% of their mean value.

Reference PMP	PN-PEMS bbsabz	Difference (±15%)
8	460	-
1.06×10^4	1.19×10^4	12.3%
1.06×10^5	1.07×10^5	0.9%
5.01×10^5	5.11×10^5	2.0%
1.08×10^6	1.12×10^6	3.7%
5.10×10^6	5.48×10^6	7.5%
1.05×10^7	1.01×10^7	-3.8%
4.20×10^7	4.23×10^7	0.7%

	$\left| \chi_{min} \times (a_1 - 1 + a_0） \right|$	Slope a_1	SEE	r^2
Threshold	≤5% max	0.85-1.15	≤10%	≥0.950
Measured	0.0% χ_{max}	1.01	0.6%	1.000

The slope can be applied at the PN-PEMS (i.e. correction 1/1.01=0.99) but it is not necessary.

Max allowed concentration for this system: 4.2×10^7 p/cm^3.

The efficiency is conducted with monodisperse aerosol and the PN-PEMS is measuring above its detection limit (**Table 7.5**).

Table 7.5: Efficiency check of the PN-PEMS (monodisperse aerosol) for one dilution setting.

Size [nm]	Doubly charged	Correction	Efficiency corr.	Limits
15				n.d.
23	0.9%	-0.8%	0.23	0.2 – 0.6
30	1.3%	-0.6%	0.37	0.3 – 1.2
50	5.7%	-2.1%	0.73	0.6 – 1.3
70	17.0%	-1.8%	0.89	0.7 – 1.3
100	22.2%	-7.6%	0.93	0.7 – 1.3
200	7.8%	-4.2%	1.54	0.5 – 2.0

8 Conclusions

This report summarized the calibration requirements of PN-PEMS. Although the principles are described in the regulation, in practice some difficulties can be encountered during the application of the procedures. In this report examples of experimental setups were given and possible combinations of calibration ways were discussed.

The main conclusions are:

The efficiency requirements have to be checked with monodisperse aerosol. This can be done for the complete PN-PEMS or its parts separately. In the second case the efficiencies have to be multiplied to each other.

The linearity requirements can be checked with monodisperse or polydisperse aerosol. In practice polydisperse aerosol is used to achieve a high concentration range. Typically the whole PN-PEMS is checked for linearity. Alternatively the particle detector can be checked separately.

The results of these checks need to be within the technical requirement specifications. There is no need to adjust the PN-PEMS or its parts; nevertheless it is permissible. With any adjustment, both linearity and efficiency still need to be within the limits.

The effect of multiply charged particles can be significant and should be taken into account. The effect can be minimized by choosing the right size distribution and reference instrument for each case.

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List of abbreviations and definitions

APG   AVL Particle Generator

CAST   Combustion Aerosol Standard

CPC   Condensation Particle Counter

DC   Diffusion Charger

DMA   Differential Mobility Analyzer

HEPA   High Efficiency Particulate Air Filter

PEMS   Portable Emissions Measurement System

PN   Particle Number

WLTC   World Harmonized Test Cycle

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