Portable Nano-Particle Emission Measurement System

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Executive Summary

Objectives

To enable PEMS4Nano to run the proposed engine and vehicle emission measurements, a suitable and calibrated Condensation Particle Counter (CPC) for PEMS use is necessary. This instrument (short name "10 nm PEMS CPC") must be optimized by PEMS4Nano partner TSI to achieve a particle detection efficiency (D_{50}) less than 10 nm for "soot-like" particles. An initial calibration must be carried out to document the instrument's performance. This initial calibration for the PEMS instrument is done with thermally conditioned, CAST-generated flame soot particles as calibration aerosol. This ensures comparability with the calibration of 23 nm PEMS CPCs as used for measurements according e.g. EURO 6d.

After the initial calibration, the instrument (integrated into a Horiba OBS-One instrument) is handed over to PEMS4Nano partner Horiba (Oberursel, Germany) for further tests and for integration of the device into the 10 nm PEMS measurement system.

Method

A 23 nm CPC (TSI PEMS-CPC as used in Horiba OBS-One series) was used as the base for optimization. Saturator-temperature and condenser temperature of the instrument had to be changed to reach the target particle detection efficiency for thermally conditioned CAST flame soot of greater than 50 % at 10 nm. Since this change in temperatures also results in a change of the instrument's characteristic condensation droplet size, the particle concentration dependent coincidence error changes compared to a 23 nm CPC. The concentration response linearization must be altered to account for this effect. Other characteristics of the instruments may suffer as well when decreasing the detection limit for particle size: The consumption of working fluid (isopropyl alcohol, IPA) will increase while the allowed window of (environmental) operating temperatures will decrease. These changes are important to determine necessary improvements for a future commercial 10 nm PEMS CPC. They will be determined and documented for the original instrument settings (D_{50} = 23 nm) and the settings optimized for D_{50} ≤10 nm.

After optimizing the settings of the 10 nm PEMS CPC to achieve a D_{50} of less or equal 10 nm together with the required linearity of response in an iterative process, the initial calibration measurements were carried out. The detection efficiency measurements were run against a Faraday cup aerosol electrometer (FCAE), an Ultrafine CPC (TSI Model 3776), or a TSI CPC Model 3772 as reference detector.

To characterize the 10 nm PEMS CPC, the detection efficiency was measured at several particle sizes (7 nm, 8 nm, 9 nm, 10 nm, 11 nm, 12 nm, 14 nm, 18 nm, 23 nm, 30 nm). At 55 nm and 70 nm, the linearity of the response of the instrument to changes in particle number concentration was determined. The linearity measurements were run at nominal particle number concentrations of 0 cm^{-3}, 1,000 cm^{-3}, 2,000 cm^{-3}, 4,000 cm^{-3}, 6,000 cm^{-3}, 12,000 cm^{-3}, 18,000 cm^{-3} and 25,000 cm^{-3}. The slope of a regression line is derived from a linear regression (concentration measured by the reference instrument, REF, vs. concentration measured by the CPC under test, CPC-UT). Following the method in regulations 49 and 83, the inverse slope of the regression line is the k-factor, which must be used to correct concentration measurements by the CPC-UT.

To ensure traceability of the calibration measurements as well as their quality/validity, the test setup for the measurement of each detection efficiency value was checked for accordance with ISO 27891[1] (calibration of condensation particle counters). The principles of the same standard were applied to check the validity of the measurements (e.g. sufficient stability of the concentration of the calibration aerosol, accuracy of its size, flow splitter bias, fraction of multiply charged particles etc.). The criteria used to qualify the CPC for use in PEMS4Nano are those agreed to in WP1 and documented in D1.1. As mentioned above, the target detection efficiency at 10 nm - when measured with thermally conditioned CAST soot - was set to 50%.

Results

The particle size dependent efficiency of the 10nm PEMS CPC under test (CPC-UT) is shown in Figure 1. As can be seen, the detection efficiency at 10 nm is 52%. Accordingly, the D_{50} is at 9.6 nm.

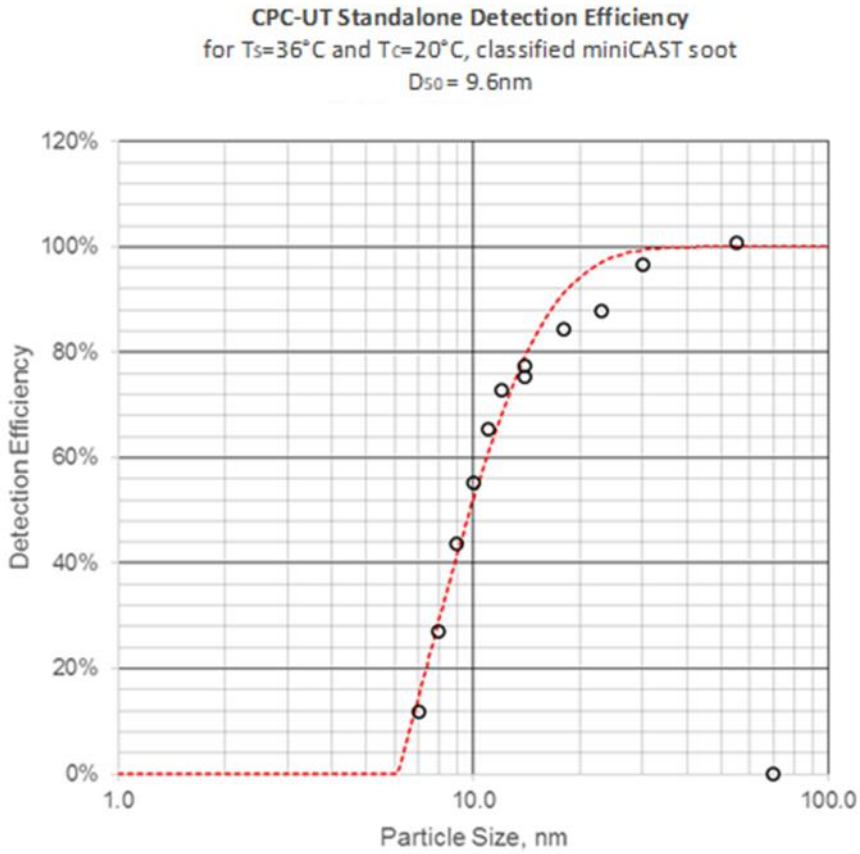

Figure 1 - Size dependent detection efficiencies of the 10 nm PEMS CPC for thermally conditioned and size classified miniCAST flame soot.

The results of the measurement of the linearity of response are summarized in Figure 2. The linear regression for concentrations measured by the reference instrument vs. the CPC-UT - applied to seven number concentrations up to approximately 23,000 cm^{-3} – results in a slope of 1.0074, compare Figure 2.

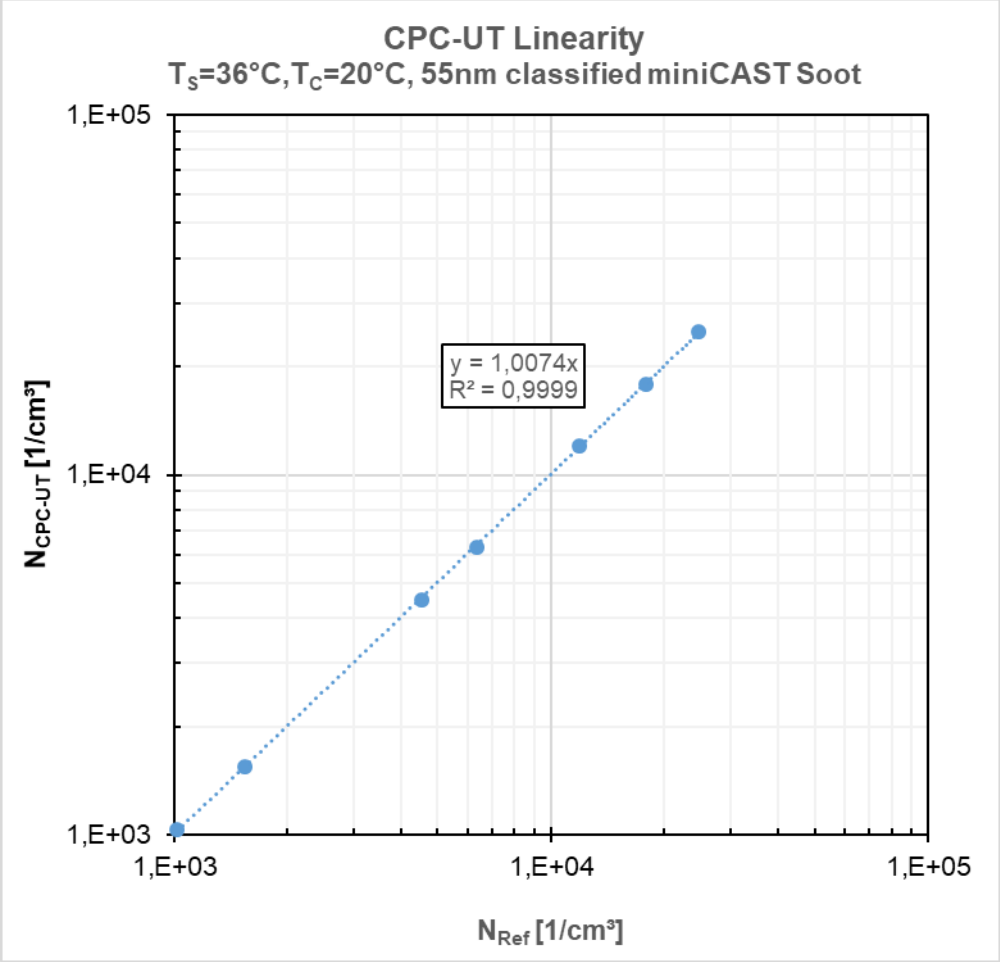

Figure 2 – Regression analysis for concentrations up to nominally 25.000 cm^{-3}

The concentration ratio of the measured, k-factor-corrected CPC-UT number concentration versus the measured reference instrument number concentration is shown in Figure 3. As can be seen from this figure, the concentration error (expressed as residual or deviation from the regression line) is less than 2% for all measured concentrations.

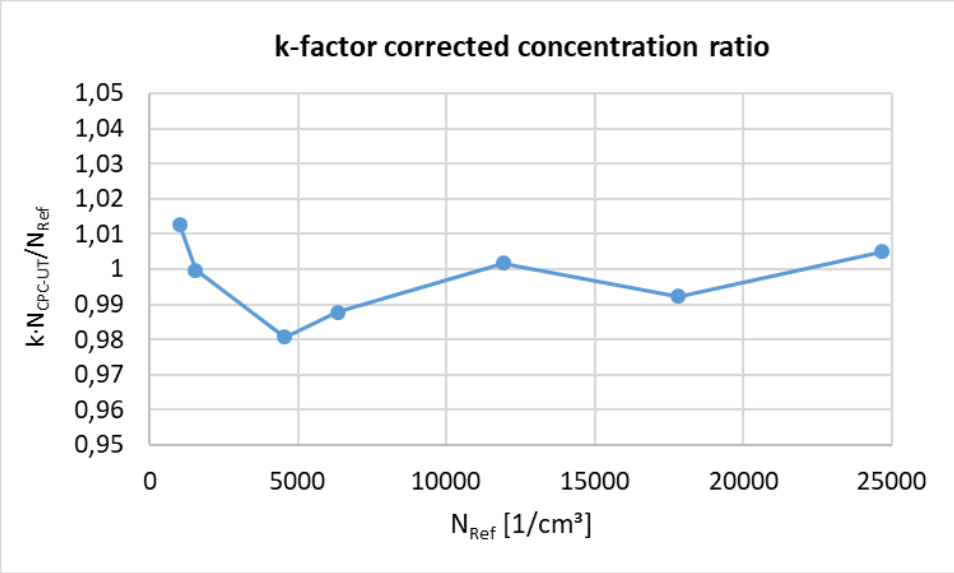

Figure 3 – Concentration ratio (k-factor corrected $N_{CPC\text{-}UT}$ / N_{Ref}) for the measured concentration range at a particle size of 55 nm.

Finally, additional linearity measurements were made with size classified 70 nm particles. The k-factor derived with the 55 nm particles was applied in this measurement. The results are shown in Figure 4.

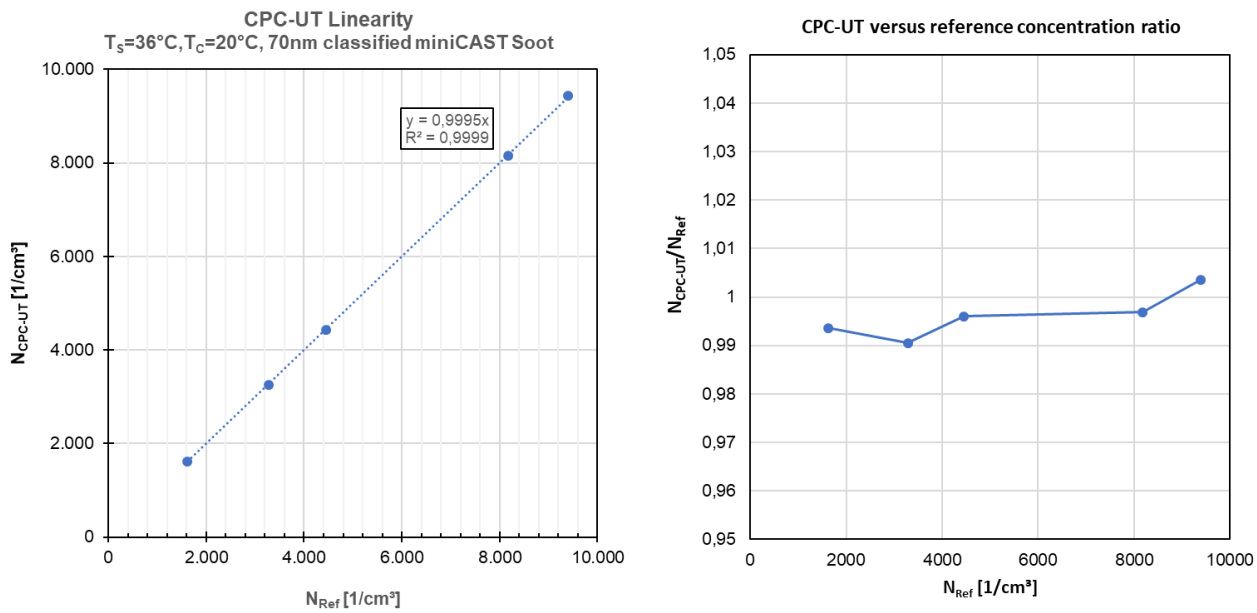

Figure 4 – Results of the linearity check with 70 nm particles.

Finally, the IPA consumption and the power consumption of the CPC-UT were measured. As expected, both the IPA consumption and the power consumption for the 10 nm PEMS CPC are increased compared to the device with settings for D_{50} = 23 nm. The IPA consumption allows operation for at least six hours. The increase in power consumption for a complete PEMS-System with built in 10 nm PEMS CPC is marginal since the biggest power sink is the heating of the sampling line.

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1 Introduction

To enable PEMS4Nano to run the proposed engine and vehicle emission measurements, a suitable and calibrated Condensation Particle Counter (CPC) for PEMS use is necessary. This instrument is called 10 nm PEMS CPC in this report. As an instrument in a calibration measurement setup, it is the CPC under test, in short called CPC-UT.

Most requirements are design criteria for the 10 nm PEMS CPC were derived in WP 1 to guarantee a simple way to integrate the CPC into the PEMS measurement system (Horiba OBS-One PN). By choosing the 23 nm TSI CPC engine, which is already used for >23 nm PEMS measurements with the Horiba OBS-One series, as the starting point for instrument optimization, these design criteria were automatically fulfilled.

The (>23 nm) CPC-100 must be optimized by PEMS4Nano partner TSI to achieve a particle detection efficiency (D_{50}) less than 10 nm for “soot-like” particles. Soot-like particles in the sense of this project are, for example, particles generated by a quenched diffusion flame aerosol generator like the Jing miniCAST.

An initial calibration must be carried out to document the instrument’s performance. This initial calibration started with an as-found measurement at the “normal” CPC settings for a 23 nm PEMS system. Next, the instrument’s operating temperatures were changed to reach a D_{50} of 10 nm or less. Changes in instrument specifications like IPA consumption and electrical power consumption were determined and reported together with the results of the calibration measurements.

Instrument settings to achieve “D_{50} as small as reasonably possible” were investigated as well. However, the findings in this context are not part of this public report.

After the initial calibration, the instrument is handed over to PEMS4Nano partner Horiba (Oberursel, Germany) for further tests and for integration of the device into the 10 nm PEMS measurement system OBS-One PN.

2 Methods and results

2.1 Calibration method

2.1.1 General

A 23 nm CPC (TSI PEMS CPC) as used in Horiba PN-PEMS OBS-One was the base for CPC optimization. Saturator temperature and condenser temperature of the CPC had to be changed to reach the target particle detection efficiency of 50 % at 10 nm for thermally conditioned flame soot generated by a miniCAST aerosol generator. Since this change in temperatures also results in a change of the instrument's characteristic condensation droplet size, the particle concentration dependent coincidence error changes compared to a 23 nm CPC. The concentration response linearization must be altered to account for this effect.

As a starting point, a full calibration measurement for standard settings of the CPC (D_{50} = 23 nm) was made. An "as-found" measurement prior to the optimization of the CPC settings for D_{50} = 10 nm confirmed that the settings and calibration for D_{50} = 23 nm are still valid. After determination of the optimized CPC settings for D_{50} = 10 nm the calibration measurements are repeated for these new settings.

Goal of the calibration procedure is to

a) determine the CPC's size dependent detection efficiency at several particle sizes and a nominally fixed number concentration and

b) to characterize the instrument's response to number concentration changes of the calibration aerosol at a fixed particle size.

Figures 2-1 illustrates the setup used for the calibration measurements. Depending on the purpose of the measurement, different instruments can be used at the position denoted "Reference Instrument" in Figure 2-1. To characterize the calibration aerosol, an SMPS (DMAS in ISO terminology) may be used. For detection efficiency measurements, a Faraday cup aerosol electrometer (FCAE) is applied. For linearity measurements, a CPC 3772 (if necessary with optional diluter) is used.

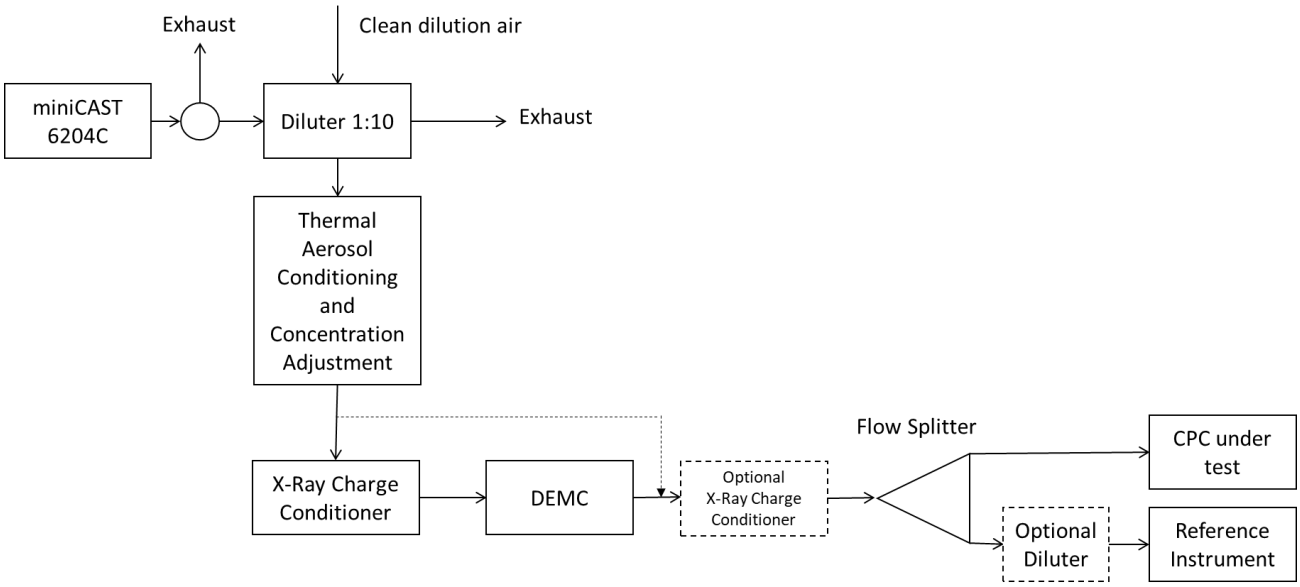

Figure 2-1 Components used for the PN-PEMS calibration measurements down to particle sizes of approximately 10 nm

A Jing miniCAST 6204C is used to produce the primary aerosol. A first diluter is used to reduce the particle concentration right after the miniCAST. This dilution reduces particle coagulation and it helps keeping a sufficient fraction of the smallest particles in the primary aerosol. Next, the aerosol passes through conditioning (a soft X-ray charge conditioner followed by thermal conditioner operated at 350 °C) and concentration adjustment (two dilution stages in series). The purpose of the soft X-ray charge conditioner is the reduction of particle charges and thus the reduction of electrophoretic losses in the conditioning and concentration adjustment system. The thermal conditioner guarantees that only solid particles are used as test aerosol. Figure 2-2 shows the conditioning and concentration adjustment in more detail.

After conditioning and concentration adjustment, the polydisperse test aerosol enters a soft X-ray charge conditioner followed by a DEMC (TSI Electrostatic Classifier Model 3782 with either a TSI long DMA Model 3081A or a TSI nanoDMA Model 3085A) which is run at a fixed voltage to let mono-mobile, classified calibration aerosol pass. This mobility classified aerosol is then run through another soft x-ray charge neutralizer (normally turned off) to a flow splitter. The flow splitter directs the aerosol to the CPC under test and to the Reference Instrument.

Alternatively, the Charge Conditioner plus DEMC can be bypassed (dashed line in Figure 2-1) to measure the size distribution of the polydisperse test aerosol with a DMAS placed in the position of the reference instrument. To extend the concentration range of the reference instrument (if necessary), an additional diluter can be used.

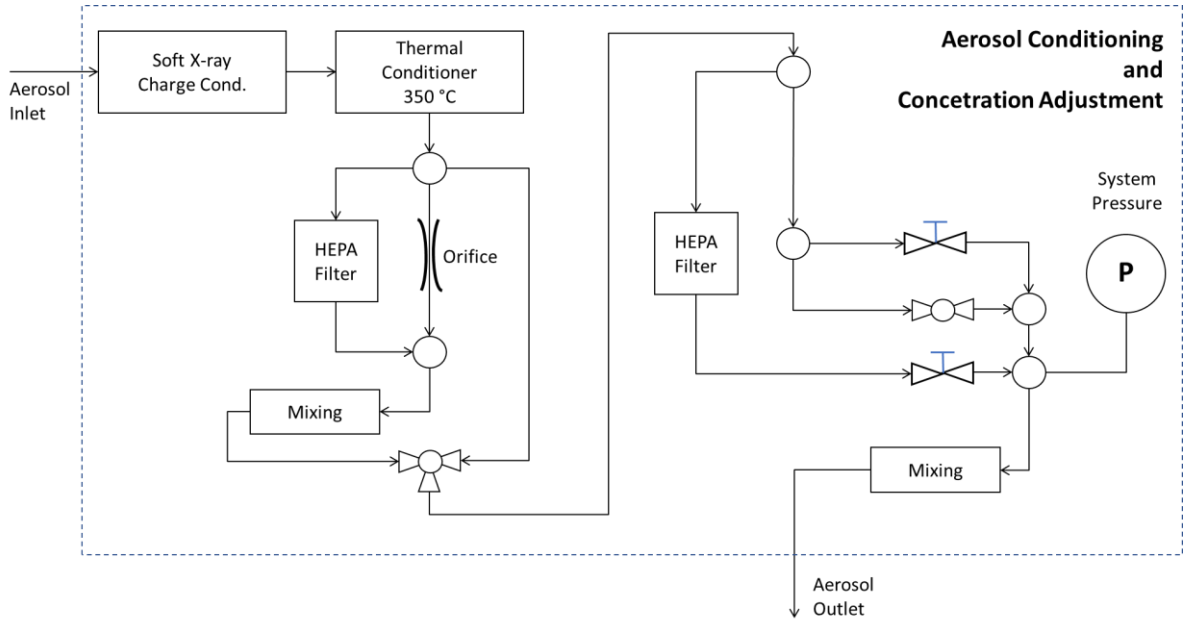

Figure 2-2 Components used for aerosol conditioning and concentration adjustment in the PEMS calibration setup for particle sizes down to approximately 10 nm (Fig. 2-1)

The calibration measurements are all based on comparing the number concentration measured by the CPC under test (CPC-UT) with the number concentration measured in parallel by a traceably calibrated reference instrument. Such comparison-based calibration measurements are standardized:

ISO 27891[1] describes

- the necessary laboratory equipment and its set-up
- requirements and tests to qualify the equipment's applicability and the integrity of the set-up,
- the calibration procedure for the determination of the detection efficiency of the CPC-UT at a given monodisperse particle size and a given particle number concentration,

- criteria to determine the validity of the detection efficiency measurement
- the calculation/estimate of the uncertainty in the detection efficiency measurement,
- the contents of calibration reports.

The instruments and tools used for the calibration measurements and their set-up are shown schematically in Figure 2-1 and 2-2. All calibration instruments and tools used for the calibration measurements had a valid, traceable calibration certificate. The reference instruments used in this setup were calibrated against a traceably calibrated master-reference (TSI electrometer 3068B calibrated by the National Physical Laboratory NPL, UK).

The calibration aerosol used for the initial calibration of the 10 nm laboratory CPC (compare deliverable report D2.02) was poly-alpha olefin PAO-4 (a/k/a Emery oil). This material is commonly used by TSI for engine exhaust CPC calibration because it offers many advantages over other aerosol materials:

- The calibration particles are spherical
  - no uncertainty due to otherwise unknown influence of particle shape on detection efficiency,
  - for d ≥ ≈5 nm, electrical mobility equivalent diameter equals geometric diameter.
- When generated with an electrospray aerosol generator (EAG) and size classified by differential electrical mobility classifier (DEMC), particles are practically all singly charged (fraction of multiply charged particles ϕ is less than 0.1 %).
- Since pre-mixed solutions are used for the EAG, changing the particle size (10 nm, 15 nm, 23 nm, 55 nm) is accomplished in some minutes.
- Since introduced for PMP-CPC calibration more than 10 years ago, the use of PAO at TSI has proven excellent repeatability and reproducibility.

Thermally conditioned (350 °C) flame soot - a different calibration aerosol - was used for the initial calibration of the 10 nm PEMS CPC. Due to its agglomerate shape, this calibration aerosol does not offer the advantages of the spherical PAO-4. However, it can be used when a catalytic stripper (CS) is connected to the 10 nm PEMS CPC; the thermally conditioned flame soot particles are stable at CS temperatures up to 350°C.

2.1.2 Preparations

The calibration setup (as described in section 2.1.1) was qualified to allow measurements fulfilling the requirements of ISO 27891[1]. This included tests such as inward leakage, overall system zero concentration, flow splitter bias and calibration aerosol stability.

Compromises were necessary for some aspects, such as the level of doubly charged particles described in section 2.1.3. While the standard requires the fraction of multiply charged particles in the monodisperse calibration aerosol to be below 10 %, this value reached approximately 15 % for mobility classified 70 nm particles. This value was, however, accepted here because (a) the CPC-UT has reached its plateau detection efficiency and (b) the reference detector used for the linearity measurements was a CPC (TSI Model 3772). The concentration measurements of both the reference instrument and the CPC-UT is not biased by the multiply charged particles.

2.1.3 Size dependent detection efficiency

Particle size dependent detection efficiency is measured with thermally conditioned, monodisperse, singly charged flame soot particles at sizes of 7 nm, 8 nm, 9 nm, 10 nm, 11 nm, 12 nm, 14 nm, 18 nm, 23 nm and 30 nm. For all sizes, the particle number concentration is set the maximum possible value. However, number concentration values above approximately 3000 cm^{-3} were not achieved due to the small particle sizes in combination with the particle generation method.

The expected fraction of multiply charged particles in the calibration aerosol downstream of the differential electrical mobility classifier (DEMC) is derived from the size distribution of the primary, polydisperse aerosol. This size distribution is measured with an SMPS after thermal conditioning and lowest possible dilution (dotted line in

Figure 2-1). Measurements to estimate the expected fraction of doubly charged particles were made with miniCAST settings for 10 nm, 15 nm, 23 nm, 41 nm and 70 nm.

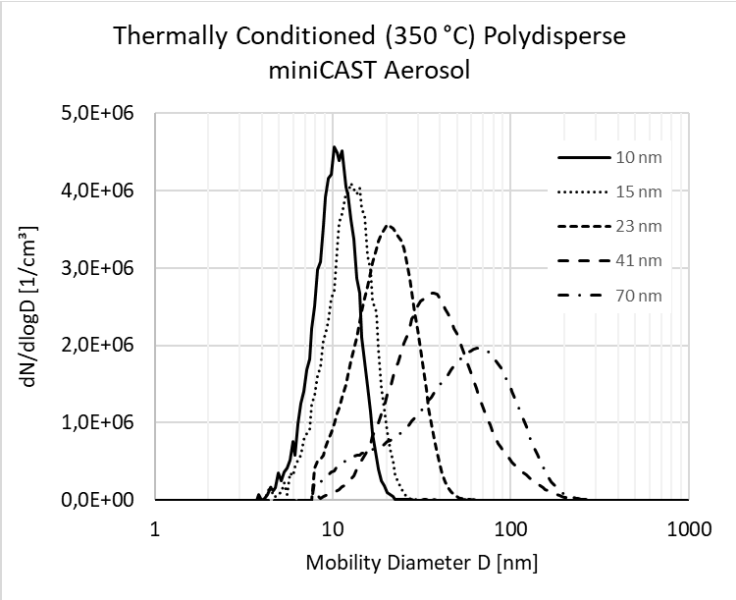

Figure 2-3 SMPS measurement of the polydisperse, thermally conditioned miniCAST flame soot aerosol with miniCAST set for CPC efficiency measurements at 10 nm, 15 nm, 23 nm, 41 nm and 70 nm, respectively.

While the number concentration of the thermally conditioned, polydisperse flame soot aerosol for CPC-UT detection efficiency measurements at miniCAST settings for 10 nm is highest, the probability for positive or negative singly charged particles at 10 nm is less than 5 %. This limits the achievable monodisperse particle number concentration after size classification to approximately 1000 particles per cm³. Typical SMPS-measured number size distributions of the thermally conditioned, polydisperse aerosol are shown in Figure 2-3. Due to the generation method of the primary, polydisperse flame soot particles with a -by far- less steep decline of number concentration with increasing particle size, doubly charged particles can no longer be neglected when this method is used. Table 2-1 shows the estimated fraction of doubly charged particles in the total, mobility classified, monodisperse calibration aerosol. In case of an FCAE used as reference instrument, the contribution of doubly charged particles must be corrected, at least for particles largen than 23 nm. If a CPC is used as the reference instrument, the fraction of doubly charged particles may be ignored once the CPC-UT has reached its plateau efficiency region (D larger than approximately 30 nm) because the doubly charged particles do not change the result of the detection efficiency measurement.

Table 2-1 Expected number concentration of monodisperse calibration aerosol and fraction of doubly charged particles, derived from the number size distributions measured by SMPS (see Fig 2-3). The fractions of charged particles f_p for soft X-ray charge conditioners under steady state conditions [2] are applied.

$D_{p=1}$ [nm] of singly charged particles	$f_{p=+1}$ [-]	Expected $N_{p=1}$ [1/cm³] monodisperse	$D_{p=2}$ [nm] of doubly charged particles	$f_{p=+2}$ [-]	Expected $N_{p=2}$ [1/cm³] monodisperse	% $N_{p=2}$ in N_{total}
10	0.044	1100				
15	0.069	950				
23	0.104	2800	33	0.0019	21.5	0,76
41	0.162	4950	60	0.0135	270	5,17
70	0.210	6400	104	0.042	860	11,9

2.1.4 Linearity of the response to changes in particle number concentration

The particle number concentration dependent detection efficiency of the CPC-UT is measured with thermally conditioned, monodisperse flame soot particles (target mobility diameter 55 nm) at concentrations measured by the reference instrument of 0, 1,000, 2,000, 4,000, 6,000, 12,000, 18,000 and 25,000 cm^{-3}.

A CPC (TSI model 3077) is used as reference instrument in this case. This ensures that multiply charged particles in the calibration aerosol downstream of the differential electrical mobility classifier (DEMC) have no influence on the result of the measurement of the detection efficiency of the CPC-UT. The reference CPC itself is calibrated against a reference electrometer.

The particle number concentrations measured by the CPC-UT are plotted against the corresponding concentrations measured by the reference instrument. A linear regression forced through zero is applied to obtain a regression line y = a * x.

- The slope a of the regression line is determined and documented.
- The k-factor (k = 1/a) is calculated and documented.
- R^2 of the linear regression is determined and documented.

For all measurements (up to nominally 25,000 cm^{-3}), the k-factor corrected concentration ratio (N_{UUT}*k / N_{REF}) is calculated and documented.

To prove the linearity measurement results, the linearity measurement (up to nominally 10,000 cm^{-3}) is repeated with thermally conditioned, monodisperse flame soot particles with a mobility diameter of 70 nm.

2.2 Results of the initial calibration of the 10 nm lab CPC

2.2.1 Original CPC settings of the PEMS CPC engine

The PEMS CPC engine used for PEMS4Nano has serial number 174902. It was first calibrated (for D_{50} = 23nm) on December 12, 2017. Conditions during this calibration were:

Temperature: 24.4 °C
Relative humidity: 24.9 %
Barometric pressure: 983 hPa

When originally set up for particle counting in a 23 nm Horiba OBS-One PN system, the following parameters which define size dependent detection efficiency were applied:

Saturator: T_S = 30°C
Condenser: T_C = 21°C

The coefficients for the polynomial function for concentration measurement linearization (coincidence correction) implemented in the firmware of the CPC were:

C_1 = 1.1076
C_2 = -3.9144 e-02
C_3 = 3.9970 e-03

As a first step, the size dependent detection efficiency and the linearity of the device were measured with the measurement setup described in section 2.1.1. For both measurements, the reference instrument was a CPC Model 3772. Figures 2-4 and 2-5 show the results of these measurements.

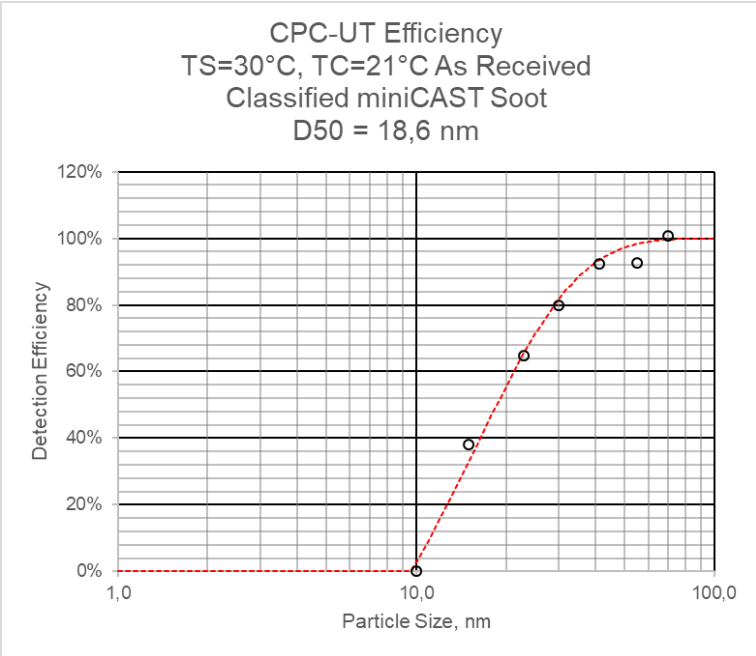

Figure 2-4 Detection Efficiency of the CPC-UT with original settings for the 23 nm OBS-One PN; measured against a CPC Model 3772 as reference instrument.

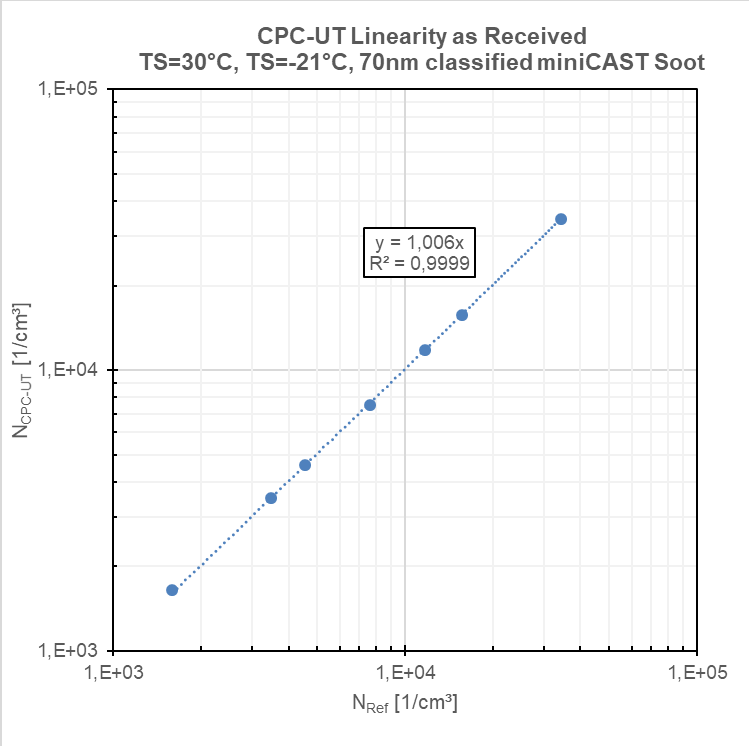

Figure 2-5 Number concentration measurement linearity of the CPC-UT with original settings for the 23 nm OBS-One PN; measured against a CPC Model 3772 as reference instrument.

2.2.2 Measurements with CPC settings for D50 ≤ 10 nm

2.2.2.1 Detection efficiency and linearity of response

In an iterative process, the temperature settings of the CPC-UT (serial number 174902, as above) were optimized. The following settings were found optimum:

Saturator: T_S = 36°C
Condenser: T_C = 20°C

The coefficients for the polynomial function for concentration measurement linearization (coincidence correction) found after optimizing for D_{50} ≤ 10 nm were:

C_1 = 1.1095
C_2 = -3.6505 e-02
C_3 = 3.5373 e-03

The above settings were stored in the firmware of the CPC-UT to change its performance as required for D_{50} ≤ 10 nm.

The detection efficiency of the CPC-UT was then measured against a TSI electrometer Model 3068B as reference instrument. The calibration particles were thermally conditioned (350 °C) flame soot particles generated with the setup described in section 2.1.1.

The calibration conditions were

Temperature: 24.7 °C
Relative humidity: 25.2 %
Barometric pressure: 984 hPa

Monodisperse calibration particles were produced by size classification in the DEMC (TSI Electrostatic Classifier Model 3082 with TSI long DMA Model 3081A) at sizes of 7 nm, 8 nm, 9 nm, 10 nm, 11 nm, 12 nm, 14 nm, 18 nm, 23 nm and 30 nm. For each particle size, 60 seconds of number concentration data derived from the zero-corrected reference electrometer current and the CPC-UT were taken. The electrometer zero current was measured intermittently for 180 seconds.

The result of the measurement of the size dependent detection efficiency of the CPC-UT is shown in Figure 2-6. A D_{50} of 9.6 nm was achieved with the CPC settings described above.

Next, a linearity test with thermally conditioned (350°C), size classified flame soot particles with a mobility diameter of 55 nm was made following the procedure described in section 2.1.4. The result of this test is shown in Figure 2-7. The regression analysis gave a slope of 1.0074 (k-factor = 0.9927) for the response to concentration changes. When this k-factor is applied to the measurements, the relative residuals compared to the regression line over the tested concentration range stay within ±2 %.

To prove the linearity measurement results, the linearity measurement (up to nominally 10,000 cm^{-3}) is repeated with thermally conditioned, monodisperse flame soot particles with a mobility diameter of 70 nm. The result of this test is shown in Figure 2-8. The k-factor obtained in the 55 nm linearity analysis is now applied. A slope of 0.9995 was found in this analysis; the relative residuals compared to the regression line were within ±1 %.

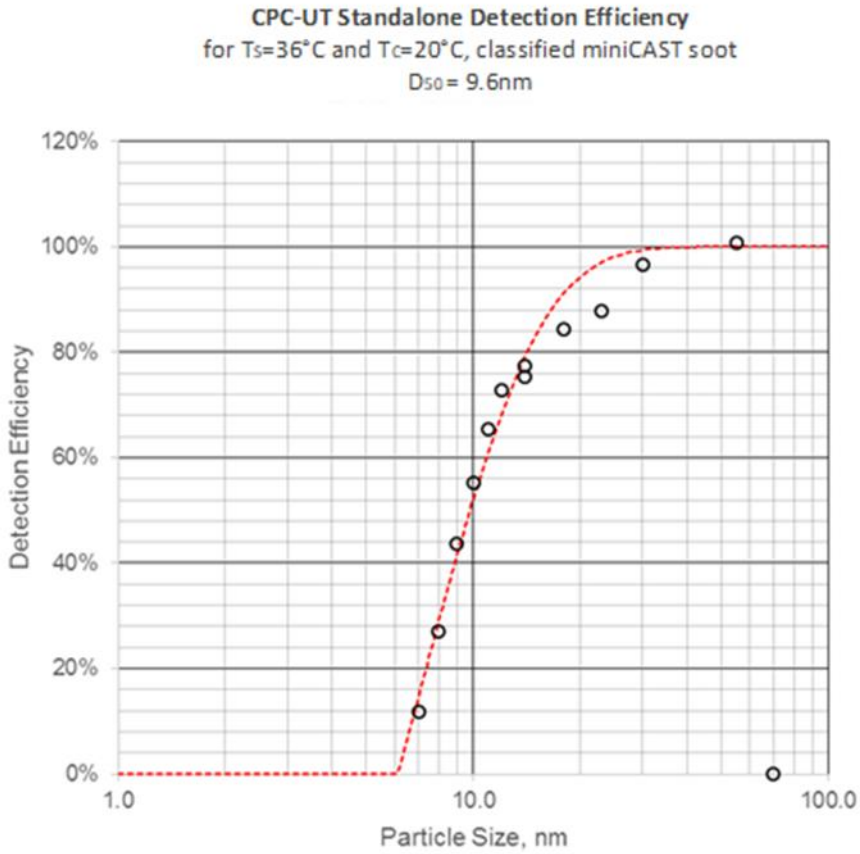

Figure 2-6 - Size dependent detection efficiencies of the 10 nm PEMS CPC for thermally conditioned and size classified miniCAST flame soot

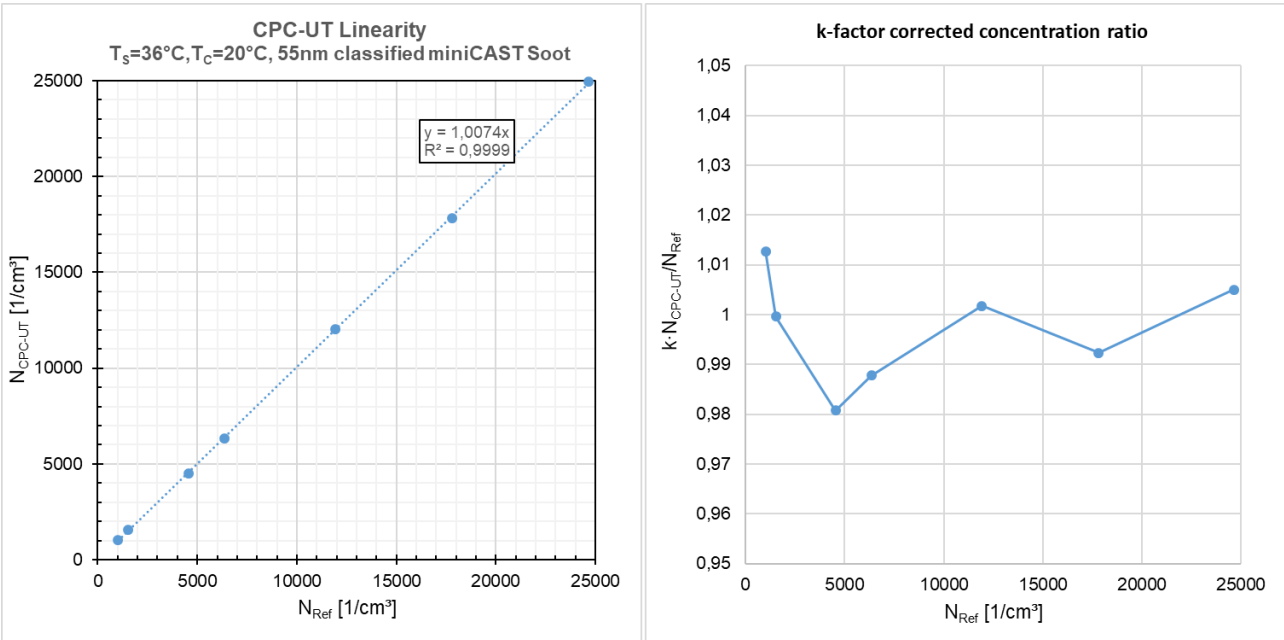

Figure 2-7 Regression analysis and k-factor corrected concentration ratio for particle number concentrations up to nominally 25.000 cm^{-3}

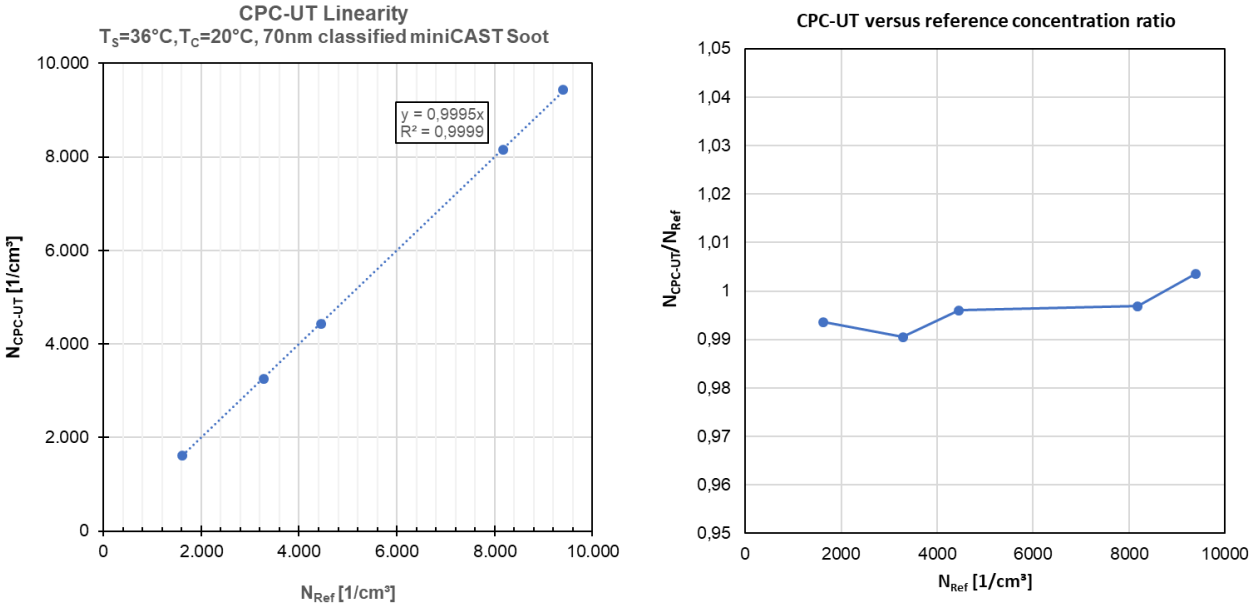

Figure 2-8 Results of the linearity check with 70 nm particles.

2.2.2.2 Consumption of working liquid and electrical power

The 10 nm PEMS CPC uses isopropyl alcohol (IPA) as working liquid. The IPA is stored in a wick inserted into the saturator of the CPC. IPA is depleted when it is condensed on the particles and this limits the possible operation time of the device. The expected operating time of CPC-UT was tested as follows:

Thermally conditioned, polydisperse miniCAST flame soot is fed to the CPC-UT and the reference instrument (via the dotted line in Figure 2-1). The CPC Model 3772 with the optional diluter was used as reference in this case. The miniCAST is set to produce a thermally conditioned aerosol with a count median diameter (CMD) of 200 nm. The number concentration of the polydisperse test aerosol is maintained close to 50,000 particles per cm³ by re-adjusting the concentration of the test aerosol, as needed, from time to time. These conditions mimic extreme operating conditions in the field.

While the IPA concentration in the saturator of the CPC-UT produces sufficient supersaturation, the detection efficiency of the CPC-UT will stay close to 100 %. When the detection efficiency drops due to IPA depletion, the IPA wick of the CPC needs re-filling. Due to the design of the 10 nm PEMS CPC, the operation must be interrupted to re-fill the IPA. Figure 2-9 shows the result of the IPA depletion test. The 10 nm PEMS CPC can be operated for at least 6 hours before IPA re-fill becomes necessary.

The power consumption of the 10 nm PEMS CPC is highest at start-up, when the operating temperatures in the instrument must be reached. The power consumption was measured with the CPC-UT installed in the OBS-One PN. The Catalytic Stripper in the OBS-One PN was turned off. Figure 2-10 shows the setup used to measure the current drawn by the instrument when the voltage of the power supply is controlled to 24 V. Figure 2-11 shows the measured temperatures and the resulting current drawn by the instrument when the T_S and T_C are set for the original operation in a 23 nm OBS-One PN system. The same measurement was repeated with the new settings for $D_{50} \leq 10$ nm, see Figure 2-12. The maximum current drawn by the instrument is, in both cases, approximately 13 A. Heating the saturator to 36 °C for $D_{50} \leq 10$ nm takes 3 to 4 minutes compared to a little less than 2 minutes for the 23 nm settings. During this time, the maximum power consumed is, for both settings, 300 to 320 W.

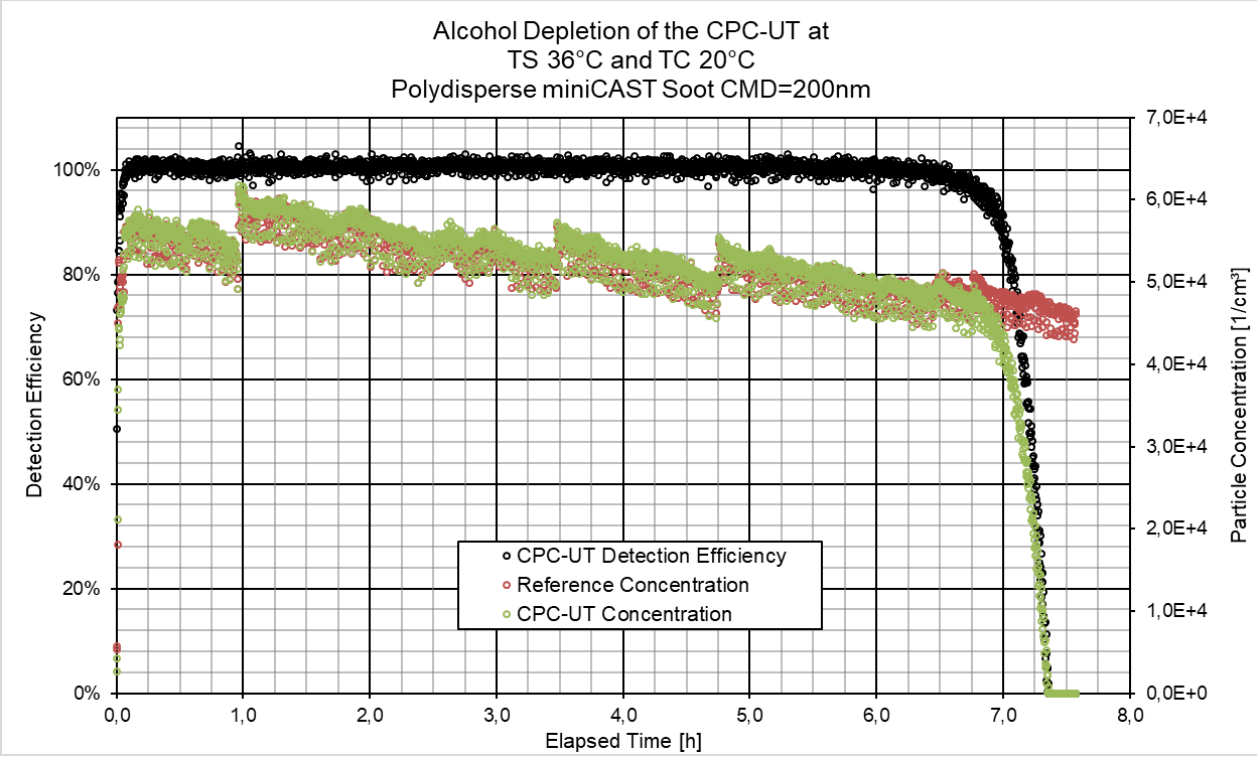

Figure 2-9 Results of the test to determine the operating time until IPA re-fill becomes necessary.

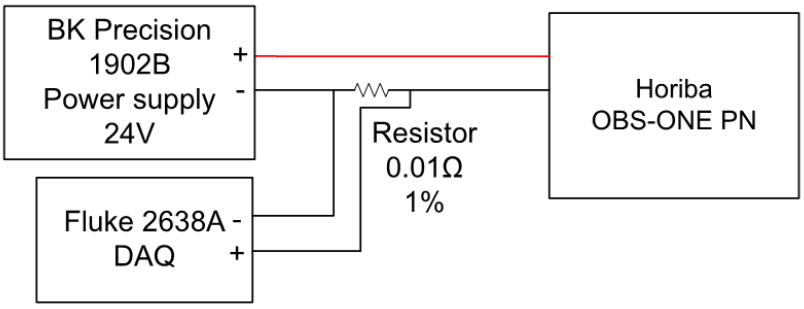

Figure 2-10 Setup to measure the current drawn by the CPC-UT when built into the Horiba OBS-One PN

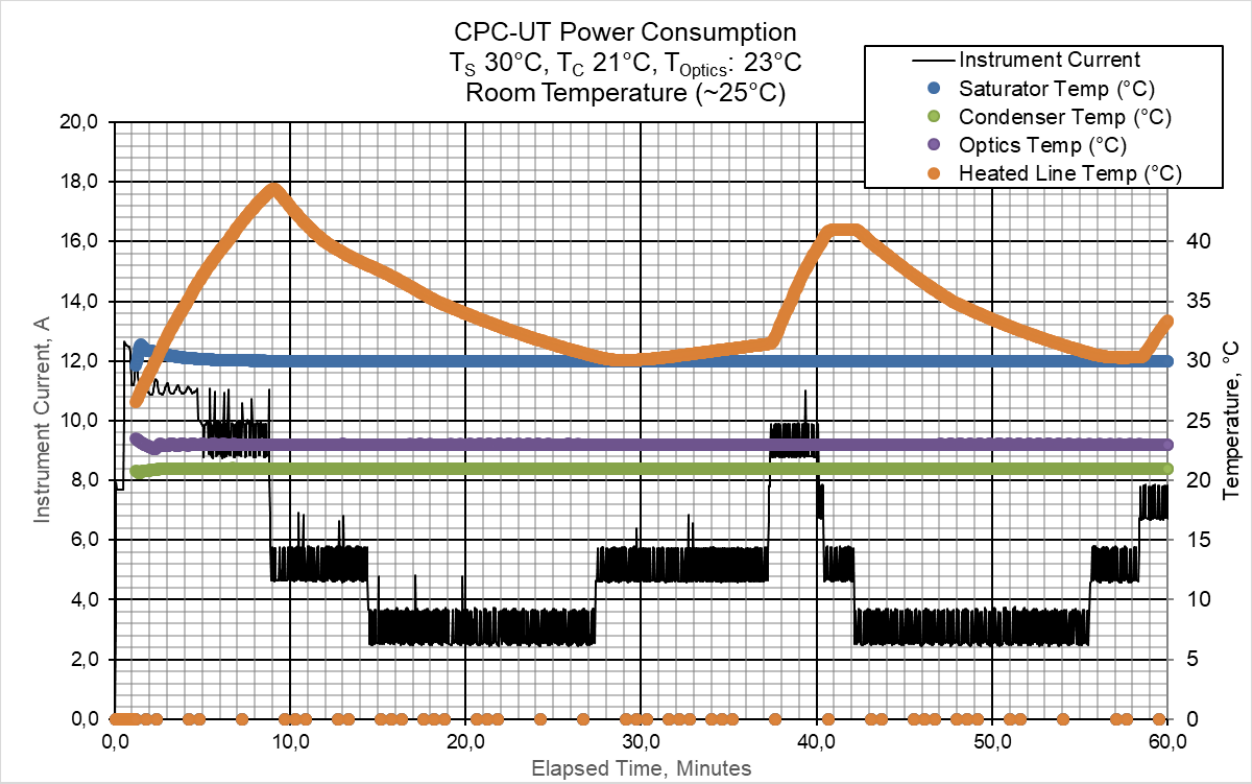

Figure 2-11 Electrical current drawn by the CPC-UT when set up for operation in a 23 nm OBS-One PN system

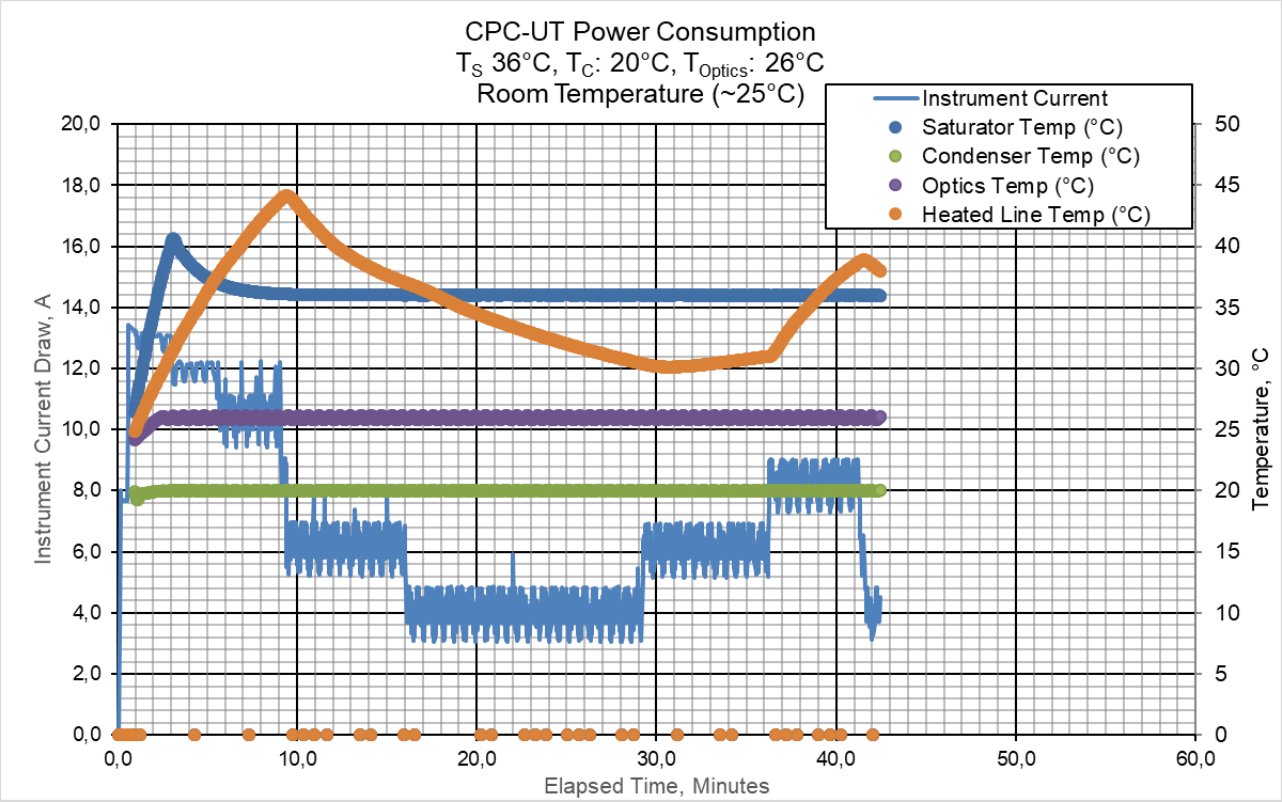

Figure 2-12 Electrical current drawn by the CPC-UT when set up for operation in a 10 nm OBS-One PN system

3 Conclusions

A CPC engine as used in the Horiba OBS-One PN for measurements of PEMS PN vehicle emissions with particle sizes larger than 23 nm was optimized for the use in a PEMS PN detecting particles of 10 nm as required for PEMS4Nano.

The optimization could be achieved by changing the operating temperatures and the coefficients of the polynomial function for linearization of the concentration measurement (coincidence error correction).

It was demonstrated in calibration measurements that a D_{50} of 9.6 nm is reached by the 10 nm PEMS CPC for thermally conditioned (350°C) miniCAST flame soot particles when applying the optimized settings.

The linearity of response to concentration changes was optimized and tested with size classified, thermally conditioned (350°C) miniCAST flame soot particles with a mobility diameter of 55 nm. For number concentrations up to approximately 25000 1/cm³ the relative residuals compared to the regression line over the tested concentration range stay within ±2 %.

The optimized instrument can be operated in a 10 nm PEMS PN system for at least 6 hours before the IPA in the instrument's wick must be re-filled.

The power consumption of the 10 nm PEMS CPC is only marginally higher than the power consumption of the 23 nm instrument. The initial heating to reach operating temperatures takes 3 to 4 minutes with the 10 nm CPC settings compared to a little less than 2 minutes with the 23 nm settings.

The optimized instrument will be ready to ship to PEMS4Nano partner Horiba Germany in time, before the end of March 2018.

4 Deviations from Annex 1

There are no deviations from Annex 1.

5 References

[1] ISO 27891-2015: Aerosol particle number concentration – Calibration of condensation particle counters

[2] Tigges, L., Wiedensohler, A., Weinhold, K., Gandhi, J. and Schmid, H.-J. (2015). Bipolar charge distribution of a soft X-ray diffusion charger. J. Aerosol Sci. 90, pp. 77-8

6 Acknowledgement

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Project partners:

#	Type	Partner	Partner Full Name
1	IND	HORIBA	Horiba Europe GmbH
2	IND	Bosch	Robert Bosch GmbH
3	IND/SME	CMCL	Computational Modelling Cambridge Limited
4	IND	TSI	TSI GmbH
5	HE	UCAM	The Chancellor, Masters and scholars of the University of Cambridge
6	HE	ULL	Université des Sciences et Technologies De Lille – Lille I
7	IND	IDIADA	Idiada Automotive Technologie SA
8	IND	HORJY	Horiba Jobin Yvon S.A.S.
9	IND/SME	UNR	Uniresearch BV

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Appendix A – Quality Assurance

Question	WP Leader	Reviewer	Technical Coordinator
	Helge Dageförde	Nick Eaves	Marcus Rieker
1. Do you accept this deliverable as it is?	Yes	Yes	Yes
2. Is the deliverable completely ready? If not, please indicate and motivate required changes.	Yes	Yes	Yes
3. Does this deliverable correspond to the DoW?	Yes	Yes	Yes
4. Is the Deliverable in line with the PEMs4Nano objectives?	Yes	Yes	Yes
a. WP Objectives?	Yes	Yes	Yes
b. Task Objectives?	Yes	Yes	Yes
5. Is the technical quality sufficient?	Yes	Yes	Yes

Appendix B – Abbreviations / Nomenclature

Table B-1 List of Abbreviations / Nomenclature.

Symbol / Shortname	
CPC	Condensation particle counter
D_{50}	Lower detection limit where the detection efficiency equals 50%
PAO	Poly-Alpha-Olefin (here: a calibration aerosol material)
FCAE	Faraday cup aerosol electrometer
REF	Index for “reference instrument”
CPC-UT	Condensation particle counter under test
k-factor	Correction factor for particle number concentration measured by the UUT, derived from calibration measurements
k	Coverage factor for measurement uncertainty
a	Slope of the regression line y = a*x
R^2	Coefficient of determination
N	Particle number concentration
$f_p(D_p)$	Fraction of multiply charged particles at a given electrical mobility equivalent particle diameter D_p for steady state conditions
D_p	Electrical mobility equivalent particle diameter
$dN/dlog(D_p)$	Number concentration size distribution function
P	Pressure
T	Temperature
RH	Relative Humidity
SMPS	Scanning Mobility Particle Sizer ™, a differential mobility analysing system (by TSI Inc., Shoreview, MN, USA)
I	Electrical current
DEMC	Differential electrical mobility classifier
DMAS	Differential mobility analysing system