Comparison of two Condensation Particle Counters for automotive applications using a combustion soot generator

Jürgen Spielvogel (2), Stefan Carli (1), Sebastian Usarek (1), Lena Brandt, (1), Lothar Keck (2), Markus Pesch (2), Hans Grimm (2), Rene Albrecht (2), Matthias Richter (2)

(1) Volkswagen AG, D-38436 Wolfsburg, (2) GRIMM Aerosol Technik GmbH & Co. KG

The Euro V regulations establish limits for the particle number concentrations in engine exhaust gas. The measurements of these particle number concentrations must be done by a standardized procedure, which specifies the dilution of the exhaust gas, the removal of the volatile aerosol fraction, and the use of a special Condensation Particle Counter (CPC) for the detection of particles. The standardization of the measurements is a work in progress in the frame of the „Particle Measurement Program“ (PMP) of the UN-ECE GRPE. The requirements for such a PMP-CPC are mainly: (1) It must be a full flow CPC, (2) the accuracy against a traceable standard must be better 10%, (3) the CPC must have a linear response ($R^2 > 0.97$), (4) the T90 response time must be less than 5 s, and (5) the counting efficiency must be of 50 +/- 12% for a particle diameter of 23 nm and > 90% for a particle diameter of 41 nm.

We have tested two commercial PMP-CPCs, namely the GRIMM model 5430 and the TSI model 3790, with the setup shown in Fig. 1. Since the characteristics of the soot particles are very similar to those emitted by combustion engines, a Combustion Aerosol Standard (CAST) soot generator (Jing Mini-CAST) was used for the generation of particles. A Vienna-type Differential Mobility Analyzer (GRIMM M-DMA) with a $^{241}\text{Am}$ Neutralizer was used to classify the particles. As a primary standard for particle number concentrations we have used a GRIMM Faraday Cup Electrometer (FCE), a GRIMM standard CPC with a minimum detectable particle size of 4.5 nm was used as additional reference and to monitor the contribution of multiple charged particles. Both FCE and reference CPC were operated with a temperature stabilized critical nozzle to maintain the flow rate with a high accuracy.

![Fig. 1: Experimental setup for the comparison of the two PMP-CPCs.](image)

Accuracy and linearity of the CPCs were determined with eight concentration steps including zero concentration for a particle size of 50 nm. The results, displayed in Fig. 2, indicate that the two tested PMP-CPCs are well within the specifications of the PMP regulations, both for
accuracy and linearity. The two PMP-CPCs feature only minor differences with the GRIMM model showing a better accuracy and the TSI PMP-CPC a slightly better linearity.

Fig. 2. Accuracy and linearity of the two tested CPCs.

Efficiency of the CPCs was alternately measured for 23 nm and 41 nm particles, each for two minutes, and the measurement was repeated 14 times to explore the reproducibility. The measured efficiencies, compiled in Tab. 1, refer to the ratio of number concentration measured by CPC and number concentration measured by FCE and constitute mean values and standard deviation from the 14 measurements.

Table 1: Efficiency of the tested CPCs. Values are in %.

<table>
<thead>
<tr>
<th></th>
<th>TSI PMP-CPC</th>
<th>GRIMM PMP-CPC</th>
<th>Reference CPC</th>
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<tr>
<td>23 nm</td>
<td>55.50 ± 0.09</td>
<td>59.84 ± 0.14</td>
<td>99.43 ± 0.11</td>
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<tr>
<td>41 nm</td>
<td>86.38 ± 0.44</td>
<td>93.59 ± 0.52</td>
<td>101.42 ± 0.61</td>
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</table>

The efficiency of the reference CPC, being essentially 100%, proves that the contribution of multiple charged particles was negligible during these measurements. Thus the combination of (1) a MiniCAST soot generator, adjusted to produce sufficiently low mean particle size and (2) a GRIMM DMA with a $^{241}$Am Neutralizer constitutes a source of monodisperse particles suitable for the calibration of PMP-CPCs. The efficiencies of the two PMP-CPCs are within the range specified by the PMP regulations with the exception that the efficiency of the TSI the TSI PMP-CPC was slightly below the required limit of 90% for 41 nm particles.

The PMP regulations do unfortunately not specify all details for the tests of a PMP-CPC and hence slightly different results from different experimental setups must be expected. This comparison showed however that two commercial PMP-CPCs feature a quite similar properties despite the different test procedures used by the manufacturers.
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Jürgen Spielvogel², Stefan Carli¹, Sebastian Usarek¹, Lena Brandt¹, Lothar Keck², Markus Pesch², Hans Grimm², Rene Albrecht² and Matthias Richter²

¹) Volkswagen AG, D-38436 Wolfsburg, Germany

²) GRIMM Aerosol Technik GmbH & Co. KG
Dorfstrasse 9, D-83404 Ainring, Germany
Email:  jsp@grimm-aerosol.com
Phone:  +49 8654 578 24
Fax:  +49 8654 578 35
Contents

PMP Measurements

Experimental Setup

- Measurements were done at Volkswagen AG, Wolfsburg, March 17, 2009

Results

- CPCs: Accuracy, Linearity, Efficiency;
  additional tests with Electrometers

Summary
# Euro 5/6 Limits for passenger cars

<table>
<thead>
<tr>
<th>Einsatzdatum</th>
<th>Diesel PM [mg/km]</th>
<th>Diesel PN [#/km]</th>
<th>Otto DI PM [mg/km]</th>
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*Reg. (EC) 715/2007*
Particle size distribution in engine exhaust gas

Source: Kittelson, 1998
Setup for PMP measurements

Particle transfer system:
Re < 1700
Residence time ≤3s

Particle concentration reduction factor calibration
99.0% reduction of > 30nm n-C40 Particles

CPC

$ \text{Particle Number Counter}$

§ <5s T90 response time
§ max. 10% coincidence correction
§ ± 10% accuracy
§ 50% efficiency at 23nm
§ > 90% efficiency at 41 nm
§ calibration with traceable standard

PND1
heats and dilutes
1:10 – 1:30

PND2
cools and dilutes
1:10 – 1:130

ET: heated Evaporation Tube

300 - 400°C

VPR
Volatile Particle Remover

150° - 400°C

HEPA

Optional carbon and HEPA filters provide particle free and low HC background air
No background correction allowed for type approval

Chinese Hat or Cyclone
Provides a cut-point at 2.5µm - 10µm

• whole system response time < 20s

*ECE/Trans/WP.29/GRPE/2007/8/Rev.1 (Reg 83 Amendment Proposal)
Main requirements for PMP-CPCs

- full flow CPC.
- **Accuracy** against a traceable standard better 10%.
- The CPC must have a **linear response**.
- T90 response time less than 5 s.
- The counting **efficiency** must be:
  - $50 \pm 12\%$ for a particle diameter of 23 nm,
  - $>90\%$ for a particle diameter of 41 nm.
Instruments used in this study

- PMP-CPC TSI 3790
- PMP-CPC GRIMM 5430
- DMA GRIMM 55-U
- Jing miniCAST Soot Generator
- FCE GRIMM 5705
Setup at Volkswagen AG

Soot Generator

Neutralizer

DMA

Flow Splitter

TSI PMP CPC

GRI PMP CPC

GRI FCE

GRI ST. CPC or TSI FCE

Flowkontroller Generator

Concentrationsregler

GRIMM M-DMA

DMAC

Critical Nozzle for FCE sample flow

Flow Splitter

Sheath Air

C3H8 Generator

N2

dry filtered air

0.3l

20.0l

1.0l

0.3l

0.6l

1.0l

Neutrionalizer

Flow Splitter

Flowkontroller Generator

Concentrationsregler

GRIMM M-DMA

DMAC

Critical Nozzle for FCE sample flow

Setup at Volkswagen AG
Nominal particle diameter: 50 nm

Eight concentrations (including zero) were measured

CPC concentrations are compared with FCE conc.

PMP regulations require $R^2 > 0.97$ and Slope $1 \pm 10\%$
Raw Data for Accuracy and Linearity

Liniarität Minicast 17.3.09

Particle Number Concentration [1/ccm]

Time

TSI PMP-CPC: Green
Grimm PMP-CPC: Grey-blue
Grimm FCE: Standard-blue
Accuracy and Linearity: TSI PMP-CPC

\[ Y = 1.05x \]
\[ R^2 = 0.998 \]
Accuracy and Linearity: Grimm PMP-CPC

Linearität Grimm PMP

\[ Y = 1.00 \times \]

\[ R^2 = 0.996 \]
Efficiency Measurements

- Required counting efficiency of PMP-CPC:
  - 50%±12% for 23 nm particles
  - > 90% for 41 nm particles

- The efficiency is also measured with FCE as a reference.

- In order to monitor double charged particles, a standard Grimm CPC was operated parallel to the FCE.

- Practically: DMA voltage was alternately set to select 23 and 41 nm particles, change of voltage after 2 minutes
Raw data for efficiency measurements

Concentration [1/ccm] vs Time

TSI PMP-CPC: Green
Grimm PMP-CPC: Grey-blue
Grimm Standard CPC: Light-blue
Grimm FCE: Standard-blue
Results: Efficiency

- TSI PMP-CPC: Green  ~88% (41 nm), 56% (23 nm)
- Grimm PMP-CPC: Grey-blue  ~94% (41 nm), 60% (23 nm)
- Grimm Standard CPC: Standard-blue
Comparison of TSI and GRIMM FCE

Concentrations of both FCEs agree well. But we suspect that the TSI FCE overshoots at fast concentration changes.
1. Both CPCs meet the accuracy and linearity requested by PMP regulations (slope 1+-10%, $R^2>$0.97):
   - $R^2 = 0.998$, Slope 1.05 for TSI CPC 3790
   - $R^2 = 0.996$, Slope 1.00 for Grimm PMP CPC

2. Both CPCs feature the required counting efficiency for 23 nm particles (50 +- 12%):
   - 56% for TSI CPC 3790
   - 60% for Grimm PMP CPC

3. The Grimm PMP features the requirement counting efficiency for 41 nm particles (> 90 %) without any correction factors.

4. Grimm FCE and TSI FCE measure essentially the same concentration

5. The GRIMM FCE measures fast concentration changes without overshooting.
Thank you for your attention