Calibration of Engine Exhaust CPCs: Measurement Uncertainty Following ISO 27891 Procedures

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TSI Master Reference Electrometer (MRE) calibrated by the National Physical Laboratory (UK)

Master Reference Electrometer (MRE)

Measures electrical charge concentration [C/cm³]

Inlet flow $q_{CAL,\mathrm{MRE}}$ measured by NPL when $q_{calc,\mathrm{MRE}}$ is set to 1 L/min:

$q_{CAL,\mathrm{MRE}}$ = **1.0173 L/min**

Relative expanded (k=2) uncertainty $U_r(q_{CAL,\mathrm{MRE}})$ = 1.5 %

d [nm]	Nominal C_N [cm⁻³]	$\frac{C_{Q,\mathrm{MRE}}}{C_{Q,\mathrm{NPL}}}$	U_r (k=2) [%]	$\frac{C_{Q,\mathrm{MRE}}}{C_{Q,\mathrm{NPL}}} \cdot \frac{q_{calc,\mathrm{MRE}}}{q_{\mathrm{MRE}}}$	U_r (k=2) [%]
23	5000	1.015	3.0	0.998	3.35
41	5000	1.017	3.1	1.000	3.44
55	2000	1.026	3.1	1.009	3.44
	4000	1.018	3.1	1.001	3.44
	6000	1.015	3.0	0.998	3.35
	8000	1.011	3.0	0.994	3.35
	10000	1.012	3.0	0.995	3.35
69	5000	1.017	3.1	1.000	3.44
	Average Efficiency [-]	**1,016**	**3.05**	**0.9994**	
	CV	**0,45 %**			

Flow-corrected average detection efficiency $\overline{\eta}_{MRE}$ of the MRE:

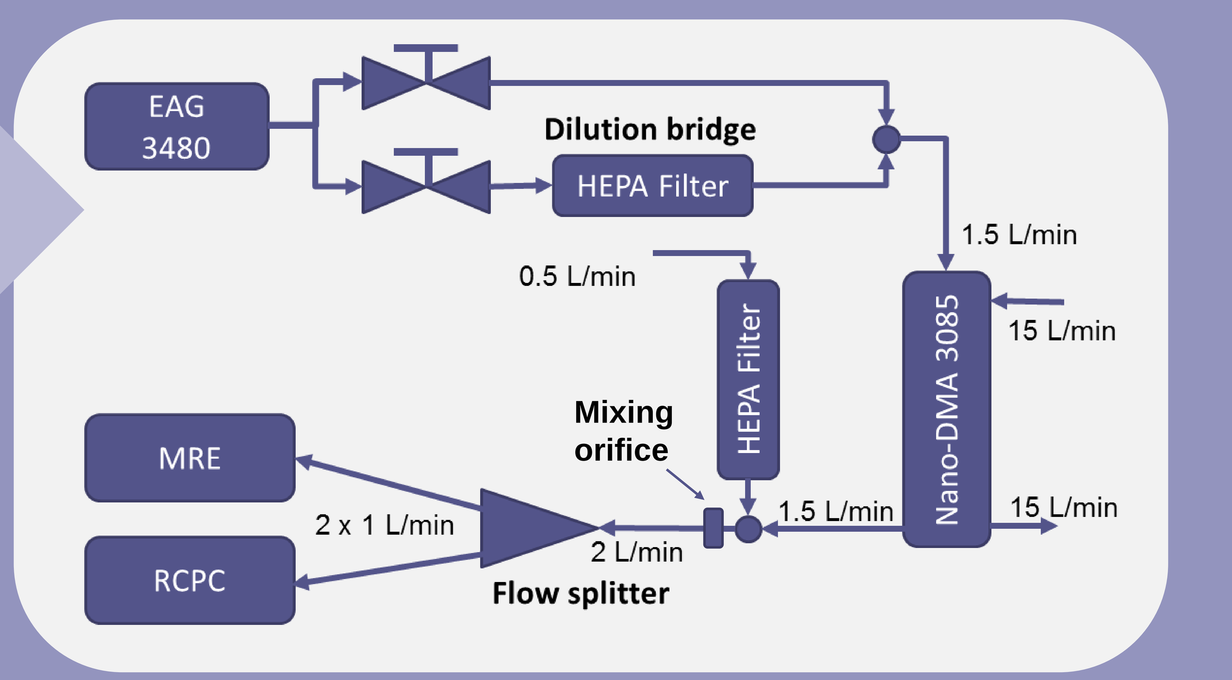
$$\overline{\eta}_{\mathrm{MRE}} = \overline{\left[\frac{C_{Q,\mathrm{MRE}}}{C_{Q,\mathrm{NPL}}}\right]} \cdot \frac{q_{calc,\mathrm{MRE}}}{q_{CAL,\mathrm{MRE}}} = 1.016 \cdot \frac{1\ \mathrm{L/min}}{1{,}0173\ \mathrm{L/min}} = \mathbf{0.9994}$$

Relative standard (k=1) uncertainty $u_r(\mathrm{MRE})$ including flow correction:

$$u_r(\mathrm{MRE}) = \sqrt{\left(\frac{U_r(\overline{\eta}_{\mathrm{MRE}})}{2}\right)^2 + \left(\mathrm{CV}\left(\frac{C_{Q,\mathrm{MRE}}}{C_{Q,\mathrm{NPL}}}\right)\right)^2 + \left(\frac{U_r(q_{CAL,\mathrm{MRE}})}{2}\right)^2} = \sqrt{\left(\frac{3{,}05\ \%}{2}\right)^2 + (0{,}45\ \%)^2 + \left(\frac{1{,}5\ \%}{2}\right)^2} = \mathbf{1.76}\ \%$$

Reference CPC (RCPC) calibrated by TSI against the TSI Master Reference Electrometer (MRE)

The MRE is used to calibrate a Reference CPC (RCPC) at TSI



$$\eta_{\mathrm{RCPC}} = \frac{C_{N,\mathrm{RCPC}} \cdot \frac{q_{calc,\mathrm{RCPC}}}{q_{\mathrm{RCPC}}}}{\frac{I_{\mathrm{MRE}}}{\mathrm{e} \cdot \overline{\eta}_{\mathrm{MRE}} \cdot q_{\mathrm{MRE}}}} \cdot \beta \cdot \sum_p \phi_p \cdot p = \boldsymbol{const} \cdot \frac{C_{N,\mathrm{RCPC}}}{I_{\mathrm{MRE}}} \cdot \overline{\eta}_{\mathrm{MRE}} \cdot \frac{q_{\mathrm{MRE}}}{q_{\mathrm{RCPC}}} \cdot \beta \cdot \sum_p \phi_p \cdot p$$

Indicated concentration of the RCPC under test
Calculated with $q_{calc,\mathrm{RCPC}}$ = 1 L/min

Nominal RCPC inlet flow
1 L/min

Concentration bias of the flow splitter
Determined experimentally

Volumetric RCPC inlet flow
Measured with Gillibrator®

Elementary charge

Indicated, zero-corrected current of the MRE

Volumetric MRE inlet flow
Measured with Gillibrator®

Contribution of multiply charged particles to I_{MRE}
Measured with Tandem SMPS

Flow corrected detection efficiency of the MRE
Taken from the MRE calibration certificate

Engine Exhaust CPC (EECPC) calibrated by TSI against the Reference CPC (RCPC)

EECPCs are calibrated against the Reference CPC (RCPC)

$$\eta_{\mathrm{EECPC}} = \frac{C_{N,\mathrm{EECPC}} \cdot \frac{q_{calc,\mathrm{EECPC}}}{q_{\mathrm{EECPC}}}}{\frac{C_{N,\mathrm{RCPC}}}{\eta_{\mathrm{RCPC}}} \cdot \frac{q_{calc,\mathrm{RCPC}}}{q_{\mathrm{RCPC}}}} \cdot \beta = \frac{C_{N,\mathrm{EECPC}}}{C_{N,\mathrm{RCPC}}} \cdot \eta_{\mathrm{RCPC}} \cdot \frac{q_{\mathrm{RCPC}}}{q_{\mathrm{EECPC}}} \cdot \beta$$

Since the efficiency curve of the EECPC is already (nearly) flat at 41 nm, and since the reference instrument is a CPC, the influence of multiply charged particles can be neglected.

Example: EECPC detection efficiency at 41 nm

Determination of q_{RCPC}, q_{EECPC} and $u_r(q_{\mathrm{RCPC}}/q_{\mathrm{EECPC}})$ from five flow measurements over 15 minutes

Run #	q_{RCPC} [L/min]	q_{EECPC} [L/min]	$q_{\mathrm{RCPC}}/q_{\mathrm{EECPC}}$ [-]
1	1,015	0,9910	1,024
2	1,015	0,9896	1,026
3	1,014	0,9891	1,025
4	1,011	0,9886	1,023
5	1,012	0,9889	1,023
Average	**1,013**	**0,9894**	**1,024**
CV		0,10%	**0,13%**

$$u_r\left({}^{q_{\mathrm{RCPC}}}/_{q_{\mathrm{EECPC}}}\right) = \mathrm{CV}\left({}^{q_{\mathrm{RCPC}}}/_{q_{\mathrm{EECPC}}}\right) = \mathbf{0,13}\ \%$$

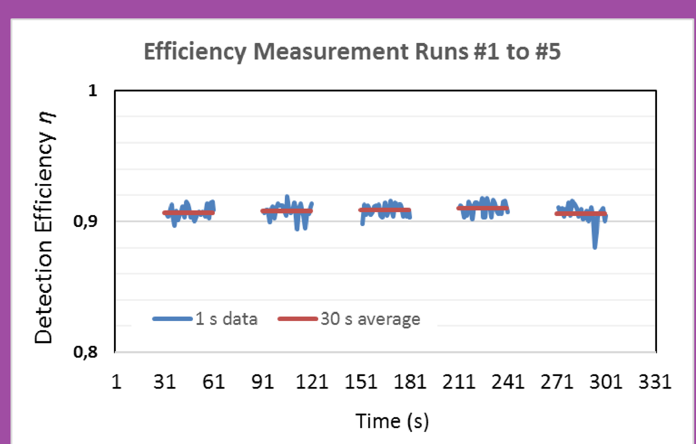
$$q_{\mathrm{RRCPC}} = \mathbf{0,9894\ L/min}$$

$$u_r(q_{\mathrm{EECPC}}) = \sqrt{\left(u_r(\mathrm{Flowmeter}^{*)})\right)^2 + \left(\mathrm{CV}(q_{\mathrm{EECPC}})\right)^2}$$

$$= \sqrt{(1{,}23\ \%)^2 + (0{,}10\ \%)^2} = \mathbf{1,23}\ \%$$

*) u_r(Flowmeter) = 1,23 % from the flowmeter calibration certificate

Determination of η_{EECPC} and $u_r(\eta_{\mathrm{rep}})$ from five efficiency measurement repetitions



Run #	Efficiency (30 s avg)
1	0,9068
2	0,9083
3	0,9085
4	0,9100
5	0,9057
η_{EECPC} = Average	**0,9079**
$u_r(\eta_{\mathrm{rep}})$ = CV	**0,18%**

Uncertainty component	Remark	u_r
$u_r(\eta_{\mathrm{RCPC}})$	From RCPC calibration	1,84 %
$u_r\left({}^{q_{\mathrm{RCPC}}}/_{q_{\mathrm{EECPC}}}\right)$	From repeatabilty of the ratio of the measured inlet flows (since $q_{\mathrm{RCPC}} \cong q_{\mathrm{EECPC}}$ and use of the same flowmeter)	0,13 %
$u_r(\beta)$	Determined experimentally (see RCPC calibration)	0,08 %
$u_r(\eta_{\mathrm{rep}})$	Overall repeatability, from five η_{RCPC} measurement repetitions	0,18 %

η_{EECPC} at 41 nm and 10000 cm⁻³ = **0,9079**

$$u_r(\eta_{\mathrm{EECPC}}) = \sqrt{(1{,}84\ \%)^2 + (0.13\ \%)^2 + (0.08\ \%)^2 + (0.18\ \%)^2} = \mathbf{1,86}\ \%$$

$$u_r(q_{\mathrm{EECPC}}) = \mathbf{1,23}\ \%$$

Relative expanded ($k = 2$) uncertainty U_r:

$U_r(\eta_{\mathrm{EECPC}}) = \mathbf{3,71}\ \%$ $U_r(q_{\mathrm{EECPC}}) = \mathbf{2,46}\ \%$

Example: RCPC detection efficiency at 41 nm

Determination of q_{MRE}, q_{RCPC} and $u_r(q_{\mathrm{MRE}}/q_{\mathrm{RCPC}})$ from five flow measurements over 15 minutes

Run #	q_{MRE} [L/min]	q_{RCPC} [L/min]	$q_{\mathrm{MRE}}/q_{\mathrm{RCPC}}$ [-]
1	1,021	1,015	1,0059
2	1,017	1,021	0,9961
3	1,023	1,017	1,0059
4	1,023	1,018	1,0049
5	1,024	1,020	1,0039
Average	**1,022**	**1,018**	**1,0033**
CV		0,23%	**0,41%**

$$u_r\left({}^{q_{\mathrm{MRE}}}/_{q_{\mathrm{RCPC}}}\right) = \mathrm{CV}\left({}^{q_{\mathrm{MRE}}}/_{q_{\mathrm{RCPC}}}\right) = \mathbf{0,41}\ \%$$

$$q_{\mathrm{RCPC}} = \mathbf{1,018\ L/min}$$

$$u_r(q_{\mathrm{RCPC}}) = \sqrt{\left(u_r(\mathrm{Flowmeter}^{*)})\right)^2 + \left(\mathrm{CV}(q_{\mathrm{RCPC}})\right)^2}$$

$$= \sqrt{(1{,}23\ \%)^2 + (0{,}23\ \%)^2} = \mathbf{1,25}\ \%$$

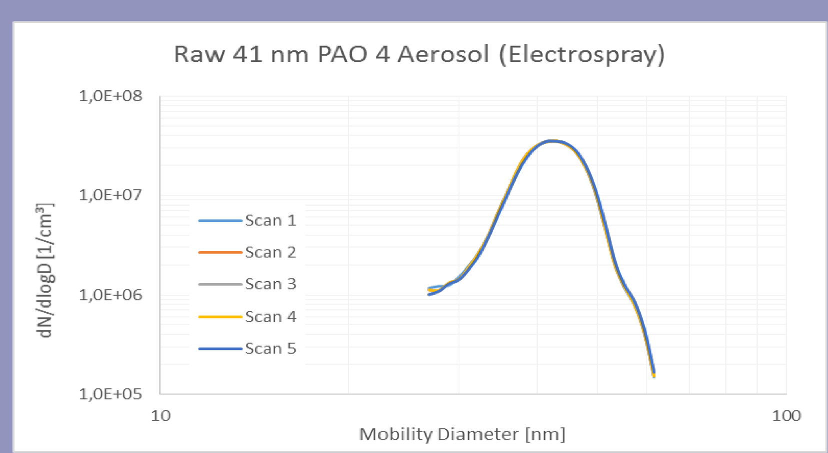
*) u_r(Flowmeter) = 1,23 % from the flowmeter calibration certificate

Determination of β and $u_r(\beta)$ by rotating four instruments (MRE, RCPC, CPC 2 and additional electrometer FCAE 2) through all four flow splitter ports; detection efficiency measurements against the MRE in all configurations

Flow Splitter Port i (with Tubing)	Normalized Efficiency $\eta_{norm,i}$ RCPC	CPC 2	FCAE 2	$\mathrm{CV}(\eta_{norm,i}) = \beta_{\mathrm{Port}}$
1	0,9967	1,002	0,9978	**0,9988**
2	1,0018	0,9990	1,0009	**1,0006**
3	1,0009	1,0023	0,9978	**1,0003**
4	1,0003	0,9963	1,0018	**0,9995**
0,999 < β_{Port} < *1,001* → β = 1,00 **$u_r(\beta)$ = CV(β_{Port}) = 0,08 %**			**CV(β_{Port})**	**0,08 %**

$$\eta_{norm,i} = {}^{\eta_{instr,i}}\Big/\left(\sum_{i=1}^{4} \eta_{instr,i}\right)/4$$

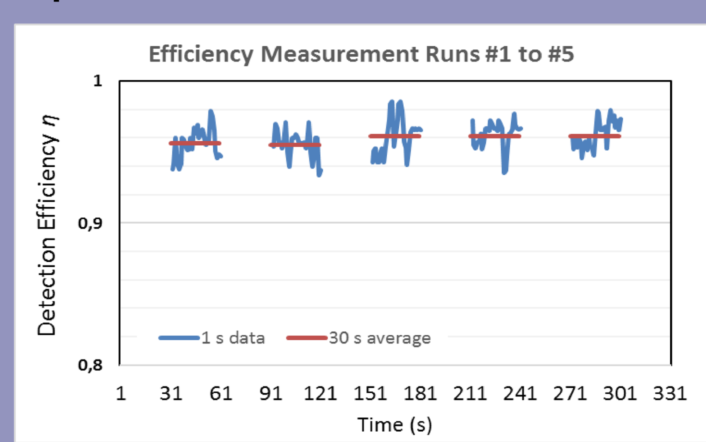
Determination of ϕ_p and $u_r(\sum_p \phi_p \cdot p)$ by tandem SMPS measurements (five repetitions)



Raw PAO4 Aerosol CMD [nm]	GSD [-]	N [cm-3]	Mobility Classified Calibration Aerosol $N(p=1)$ [cm-3]	$N(p=2)$ [cm-3]	$N(p=3)$ [cm-3]	Charge Fractions $\phi_{p=1}$	$\phi_{p=2}$
42,1	1,13	4,31E+06	9,47E+03	1,47E+01	---	9,98E-01	1,55E-03
42,1	1,13	4,31E+06	9,47E+03	1,46E+01	---	9,98E-01	1,54E-03
42,2	1,13	4,29E+06	9,39E+03	1,54E+01	---	9,98E-01	1,64E-03
42,1	1,13	4,30E+06	9,45E+03	1,46E+01	---	9,98E-01	1,54E-03
42,2	1,13	4,30E+06	9,42E+03	1,54E+01	---	9,98E-01	1,63E-03
					Average	**0,9984**	**0,00158**
					σ	**0,00005**	**0,00005**

$$u_r\left(\sum_p \phi_p \cdot p\right) = \frac{\sqrt{\left(\sigma(\phi_{p=1}) \cdot 1\right)^2 + \left(\sigma(\phi_{p=2}) \cdot 2\right)^2}}{\overline{\phi_{p=1}} \cdot 1 + \overline{\phi_{p=2}} \cdot 2} = \mathbf{0,01}\ \%$$

Determination of η_{RCPC} and $u_r(\eta_{rep})$ from five efficiency measurement repetitions



Run #	Efficiency (30 s avg)
1	0,9564
2	0,9553
3	0,9611
4	0,9609
5	0,9614
η_{RCPC} = Average	**0,9590**
$u_r(\eta_{\mathrm{rep}})$ = CV	**0,31%**

Uncertainty component	Remark	u_r
$u_r(\mathrm{MRE})$	Taken from the MRE calibration certificate	1.76 %
$u_r\left({}^{q_{\mathrm{MRE}}}/_{q_{\mathrm{RCPC}}}\right)$	From repeatabilty of the ratio of the measured inlet flows (accuracy of q is not considered here since $q_{\mathrm{MRE}} \cong q_{\mathrm{RCPC}}$ and use of the same flowmeter)	0.41 %
$u_r(\beta)$	Determined experimentally	0.08 %
$u_r\left(\sum_p \phi_p \cdot p\right)$	Determined experimentally from five Tandem-SMPS measurements *Note: Correction for double charged particles can be neglected since $\phi_{p=1}$ = 0,9984 ≈ 1,00*	0.01 %
$u_r(\eta_{\mathrm{rep}})$	Overall repeatability, from five η_{RCPC} measurement repetitions	0.31 %

η_{RCPC} at 41 nm and 10000 cm⁻³ = **0,959**

$$u_r(\eta_{\mathrm{RCPC}}) = \sqrt{(1.76\ \%)^2 + (0.41\ \%)^2 + (0.08\ \%)^2 + (0.01\ \%)^2 + (0.31\ \%)^2} = \mathbf{1.84}\ \%$$

$$u_r(q_{\mathrm{RCPC}}) = \mathbf{1,25}\ \%$$

Reference: ISO 27891-2015: Aerosol particle number concentration – Calibration of condensation particle counters (ISO TC 24/SC 4/WG 12)