Shipboard characterization of a wet scrubber system during operation (part II): Influence on particle number concentration, particle size distribution and chemical composition

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Keywords: Ship emissions, SMPS, ELPI, particle number concentration, particle size distribution, elemental analysis, particle chemistry

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Introduction

Ultrafine particles are generally recognized to have an adverse impact on human health and as result particle emissions from marine engines are coming under scrutiny. Although regulations on NO_X emission from ships have been implemented and sulphur content in marine fuel is now limited to 1.0 % in emission control areas, emissions from ship traffic is still a much debated subject, especially in harbour cities. Two mitigation strategies are presently being exploited: 1) lowering of the sulphur content in fuel and 2) implementation of emission reducing technologies such as filters and scrubbers.

In this study, emission data from a ship with a wet scrubber system installed is presented. The results are from a measurement campaign carried out October 16-18 2012 during operation between Göteborg and Gent. Data are compared with previous measurements obtained February 8-9 2011. The aim was to acquire data from longer measurement periods than in 2011 and to compare data obtained for different periods. The main focus was on measuring particle number concentration and particle size distribution before and after the scrubber system using a scanning mobility particle sizer (SMPS) and an electrical low pressure impactor (ELPI). The chemical composition of the particles was also investigated

Experimental

The main engine is a MAN B&W 9L60 MC-C , 21070 kW, 2-stroke diesel engine. The engine was run at 65-82 % of maximum continuous rating (MCR) during particle measurements. The effect of the scrubber system on the main engine emission of particles was tested for fuel containing 2.3 % (w/w) sulfur.

For particle characterization before and after the scrubber system a Scanning Mobility Particle Sizer (SMPS) from TSI and an Electrical Low Pressure Impactor (ELPI) from Dekati were used. A system based on two ejector diluters was used for diluting the gas. The first diluter was heated to 350 °C and the second was at ambient temperature. The total dilution factor was 136.

Results and conclusions

Three periods with constant engine and scrubber conditions were chosen Oct. 16 for evaluating the reproducibility of measurements after scrubber. Average particle size distributions are given in Figure 1.

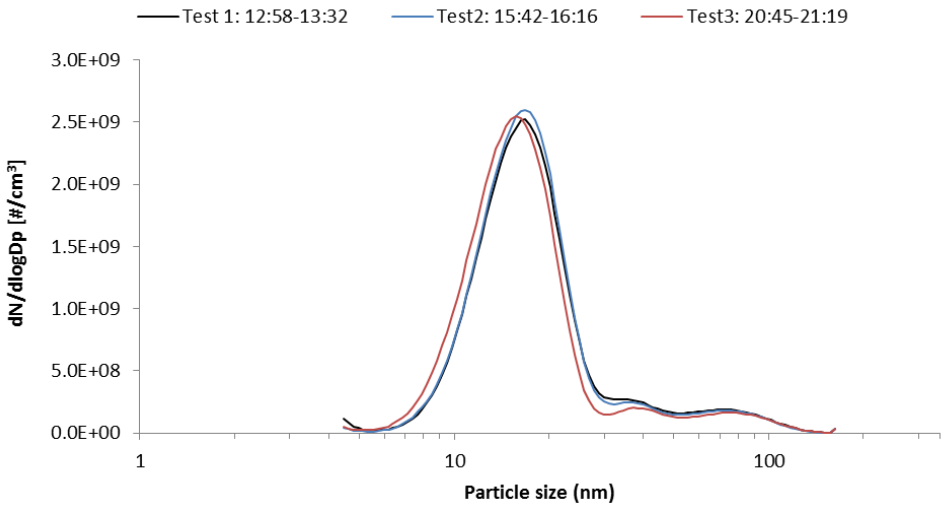


Figure 1: Average particle size distributions measured after the scrubber for three selected periods on Oct. 16

Particle measurements performed in this study show that the majority (number) of particles emitted are smaller than 30 nm. In the range of the measurement uncertainties it was found that the scrubber system decreases the emitted particulate number (PN) concentration (#/cm3) by 30-60 % under the conditions of the selected periods (visualized in Figure 2).

There is a good agreement between PN reductions calculated from integrated SMPS and ELPI data. Both PN concentration and peak particle diameter (mode1) decreases after the scrubber for all selected periods. Deviations between ELPI and SMPS in PN concentration for focus periods 4 and 5 (see Figure 2) are likely due to smaller mode1 diameter (ca. 10 nm), close to ELPI cut.

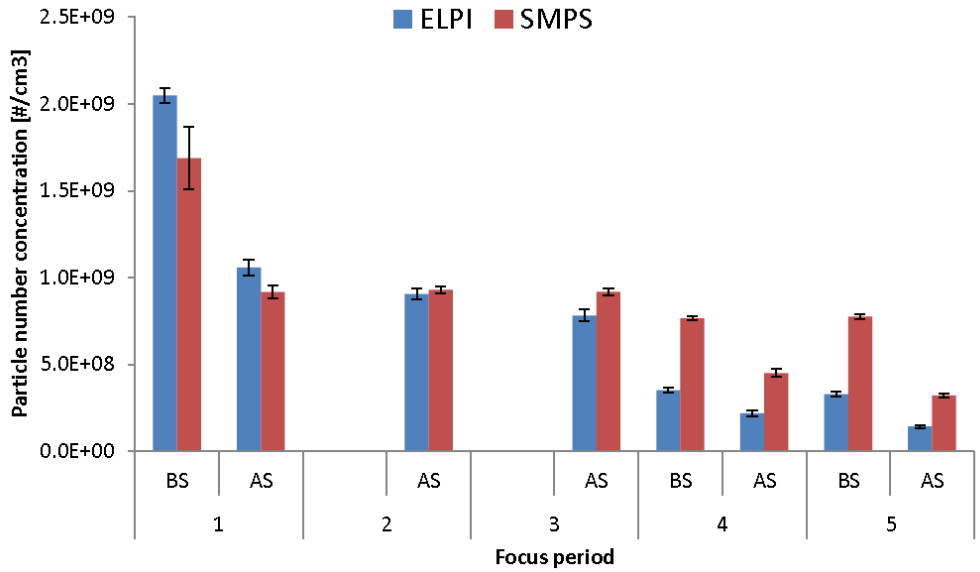


Figure 2: Particle number concentration measured before scrubber (BS) and after scrubber (AS) with ELPI (7-10,000 nm) and SMPS (4-165 nm)

In Figure 3 particle size distributions measured before and after scrubber in 2012 and 2011 are compared for selected periods with similar engine and scrubber operating conditions. For the selected periods with similar engine and scrubber operating conditions there is a good agreement with measurements carried out in Feb. 2011 (Figure 3).

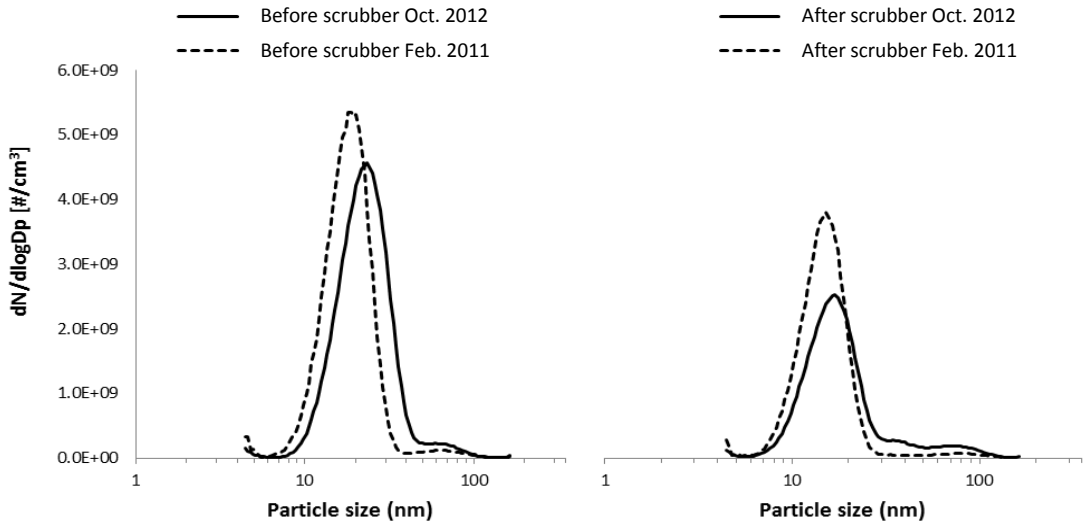
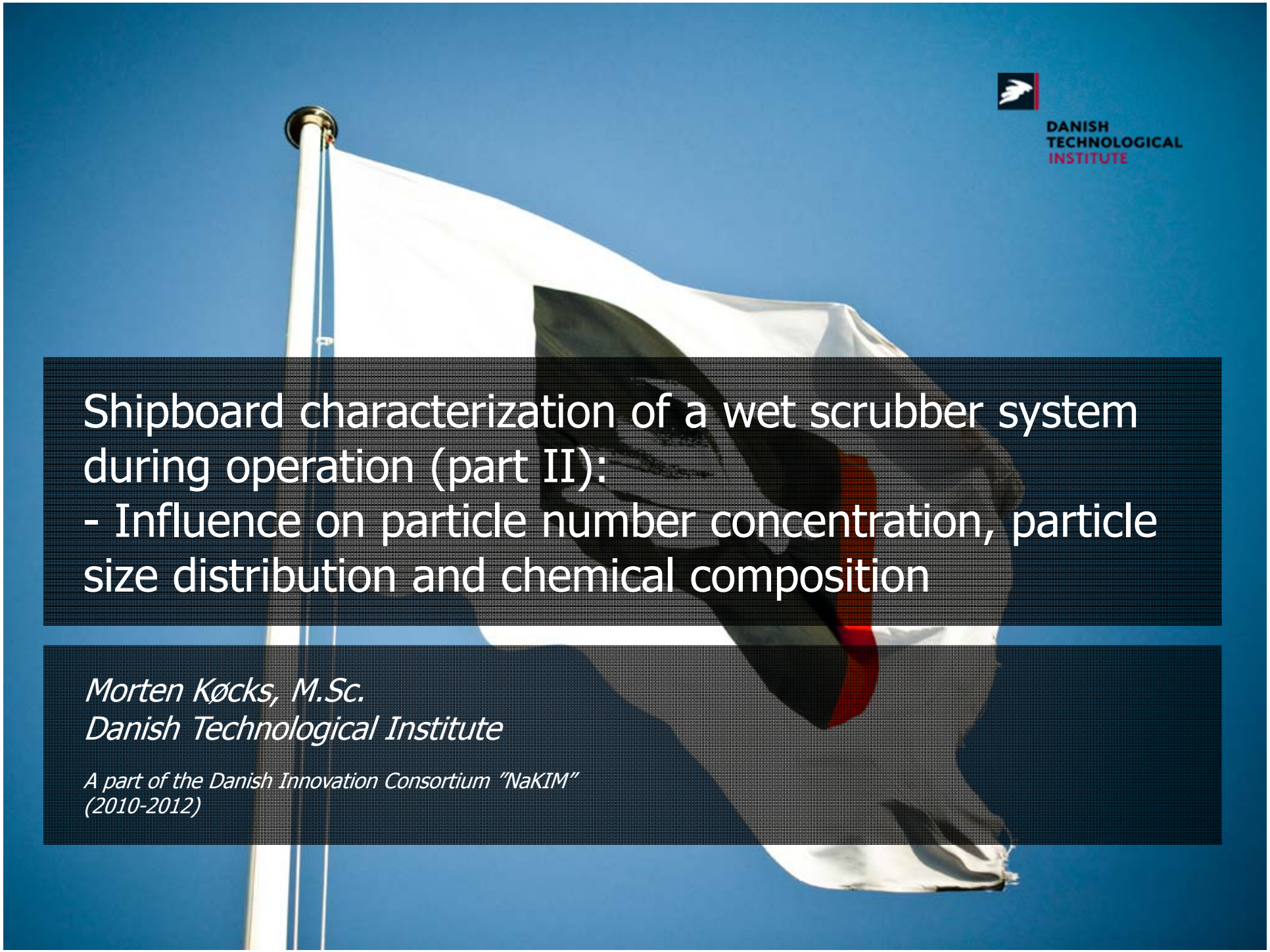


Figure 3: Comparison between results from Oct. 2012 and Feb. 2011 for fuel containing 2.3 % S

Elemental analyses of particles for two selected periods, sampled before and after scrubber respectively, show a total carbon reduction of about 50 %. Carbon dominates the particle mass. An increase in the percentage of iron, nickel, oxygen, and sodium in the particle mass was observed after scrubber; all of this in agreement with what was observed in 2011 data. The exception is iron which in the present campaign is found in significantly lower concentrations after scrubber. Chlorine is not observed, in agreement with 2011 campaign.

This work was supported by the Danish Agency for Science, Technology and Innovation and is part of the innovation consortium NaKIM



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Shipboard characterization of a wet scrubber system during operation (part II):
- Influence on particle number concentration, particle size distribution and chemical composition

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Danish Technological Institute

A part of the Danish Innovation Consortium "NaKIM"
(2010-2012)

Background

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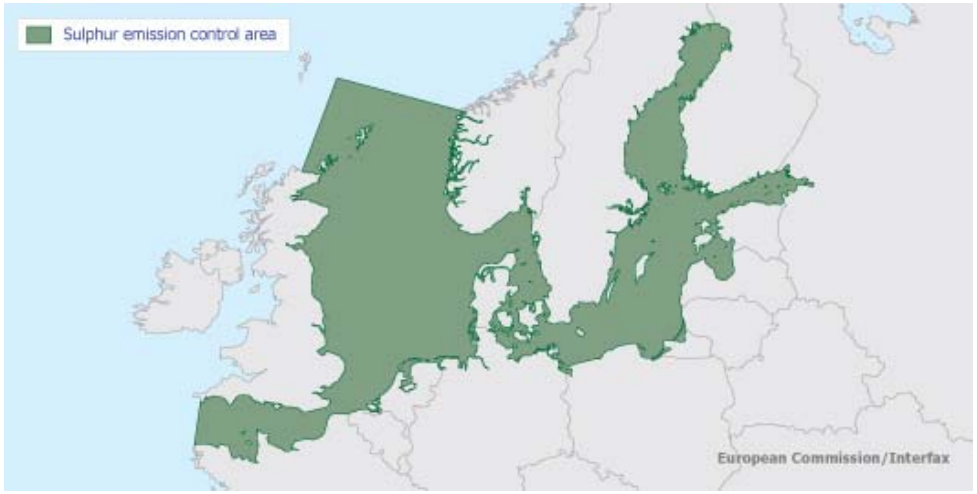
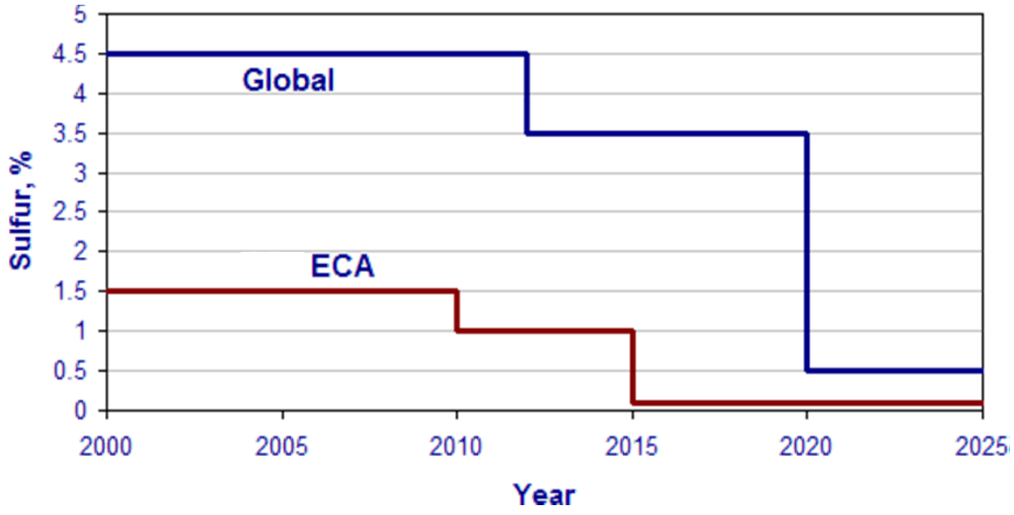
- Companies are faced with requirements relating to fuel sulphur content in ECAs (Emission Control Areas)
  - 2010: 1% sulphur (max)
  - 2015: 0.1% sulphur (max)



- Two mitigation strategies are being exploited:
  - Lowering of the sulphur-content in fuel
  - Emission reducing technologies (such as scrubbers)



Project background

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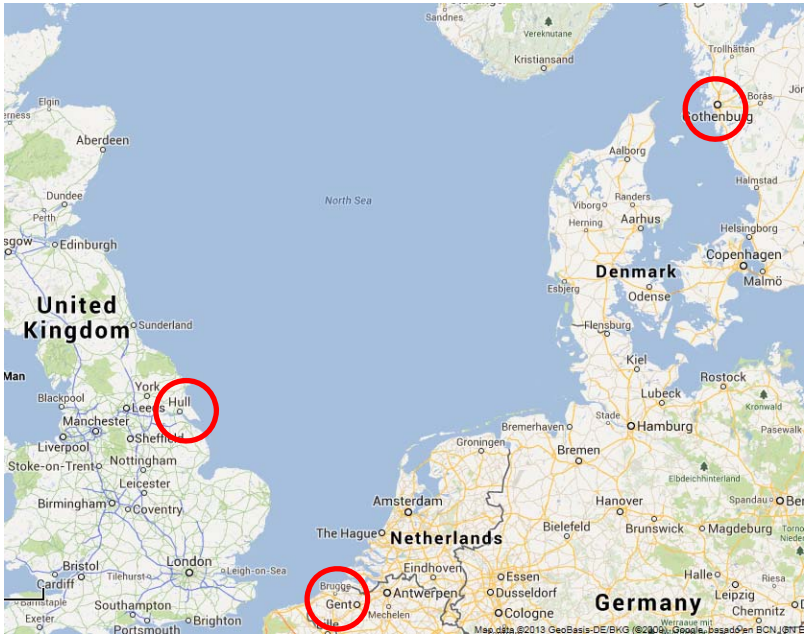
- Presently no legislation on PM/PN emission from ocean going vessels in European emission control areas. Likely to be introduced in future.

- <u>Project objective:</u>
  Evaluate methods for characterizing particle emission before/after a wet scrubber system



<u>Present campaign:</u>

Oct. 16-18, 2012 (Gothenburg-Gent)

<u>Former campaign:</u>

Feb. 8-9, 2011 (Gothenburg-Immingham)

Ficaria Seaways

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Year built	2006 (rebuilt 2009)
Length	230.43 m (199.8 before rebuilt)
Width	26.5 m
Gross tonnage	37 939 (32 389 before rebuilt)
Speed	22.5 knots
Cargo capacity	4 650 lane meters (3 831 before rebuilt)
Accommodation	12 drivers
Main engine	MAN B&W type 9L60 MC-C 21 070 kW, 2-stroke
Operation	Göteborg-Gent
Scrubber	Seawater (SW) or freshwater (FW) mode

Measurement location

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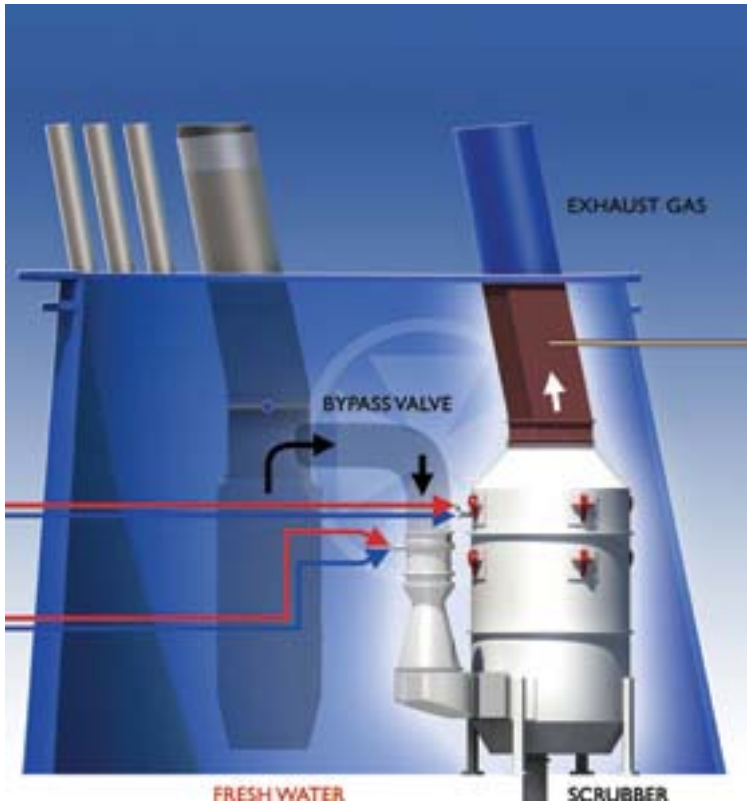
- 2.3 % S heavy fuel oil (HFO)
- Switch between measurements before and after the scrubber
- Heated probe 180 °C, cyclone 10 µm cut (D_{50})



Measurement location

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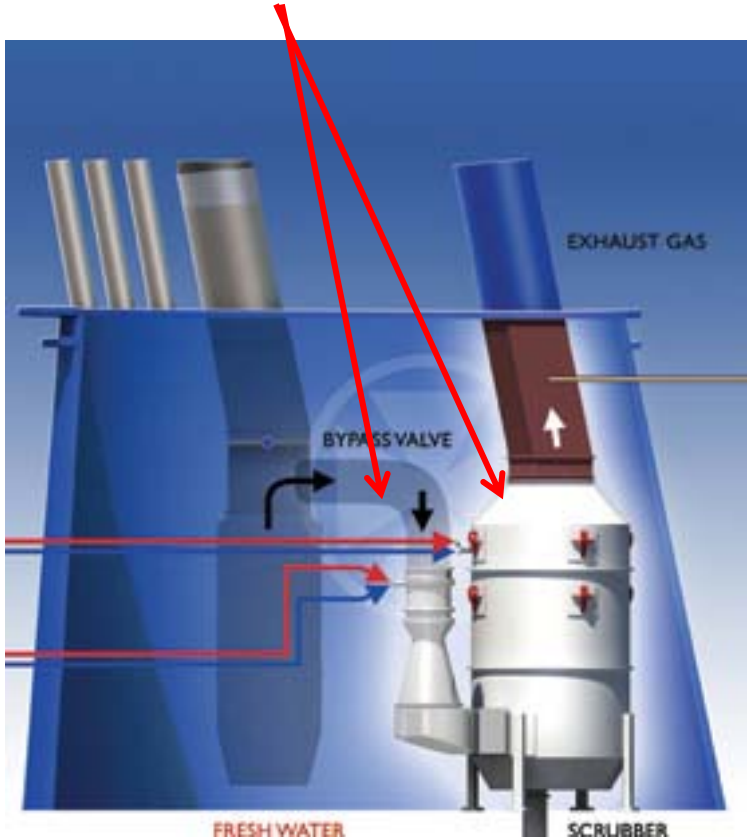
Particle measurement locations



Before scrubber

After scrubber

Experimental setup

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Measured parameters:

- Particle number concentration and size distributions
  - ELPI: 10 s intervals, 7-10,000 nm
  - SMPS: 3 min intervals, 4-165 nm
- Particle inorganic chemistry (elemental analysis) using energy dispersive X-ray spectroscopy (EDX)
- Total organic carbon (FID)

2 jet injection diluters were used.
- First dilution step 350 °C
- Second room temperature
- Total dilution factor: 136

Engine load and focus periods

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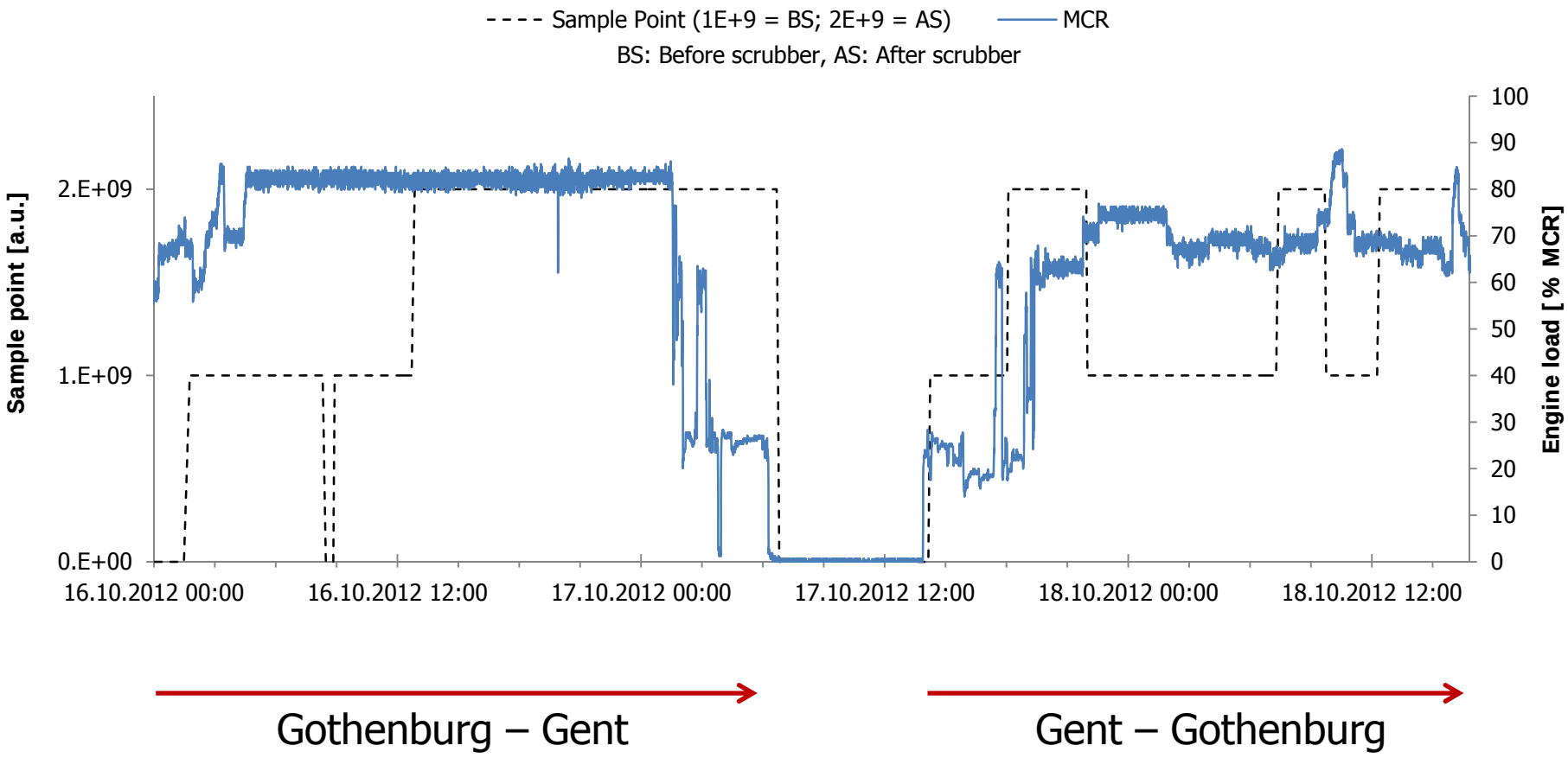

Engine load and focus periods

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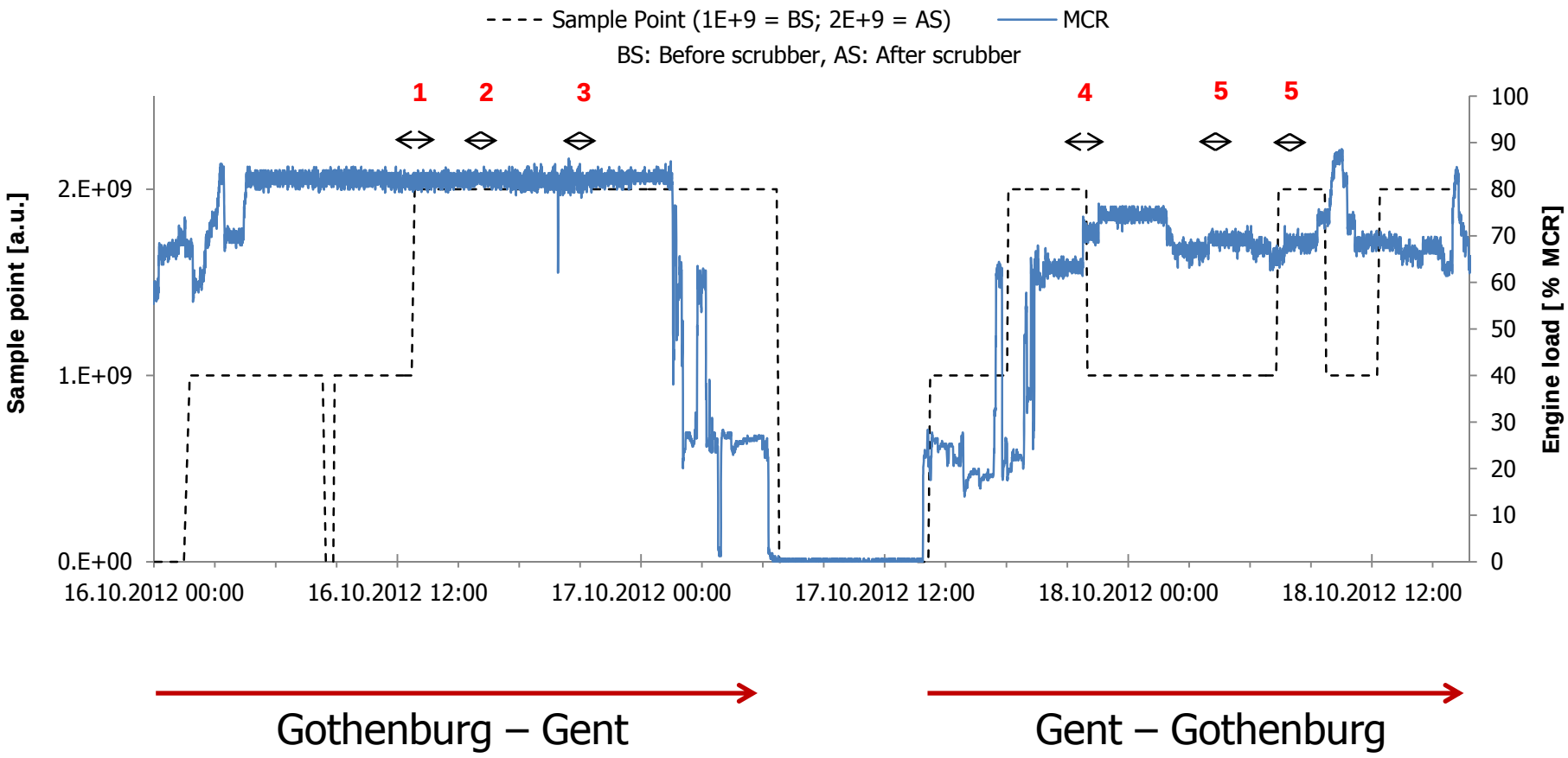

PN concentration in time

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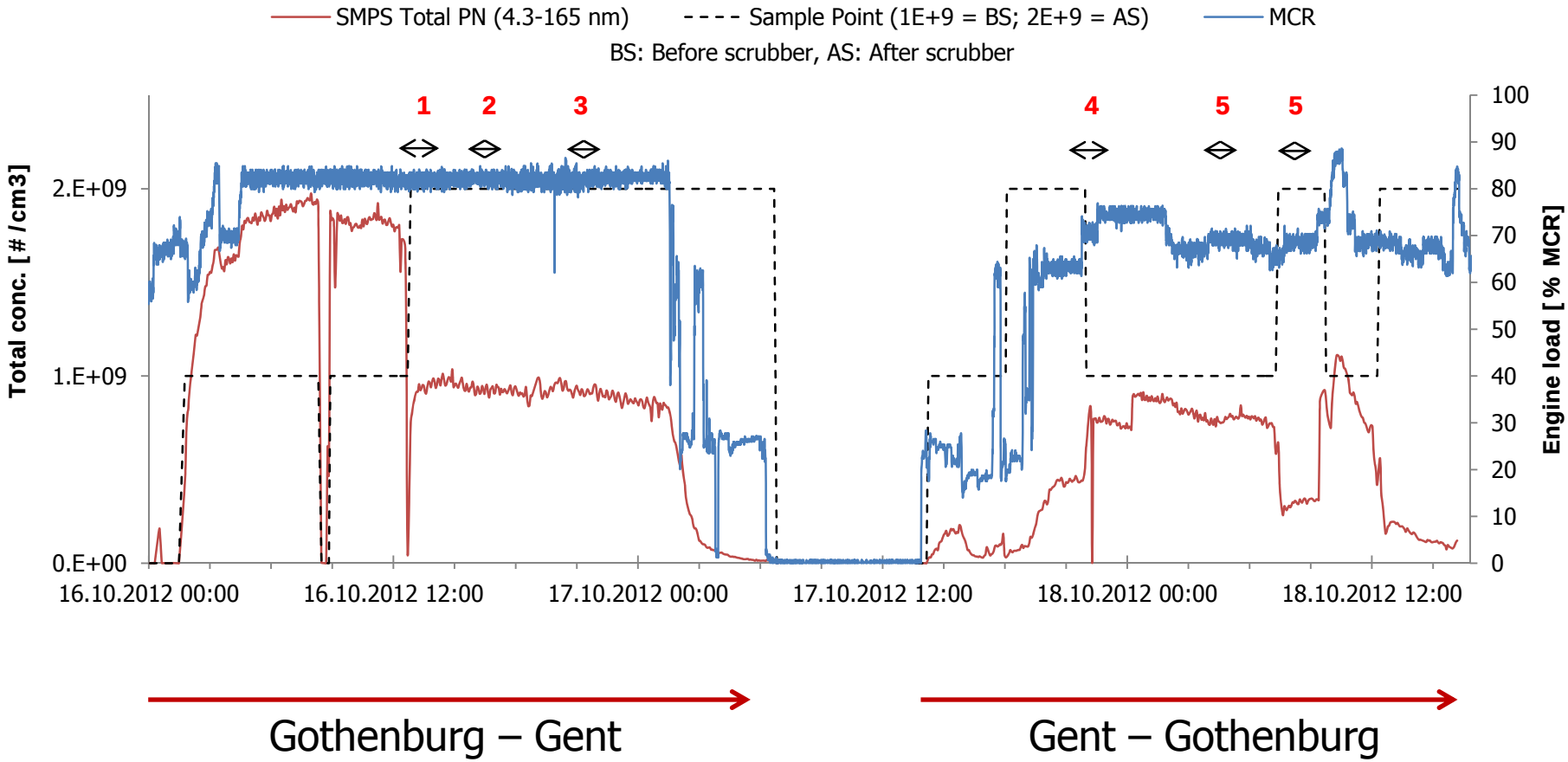

PN reduction during focus periods

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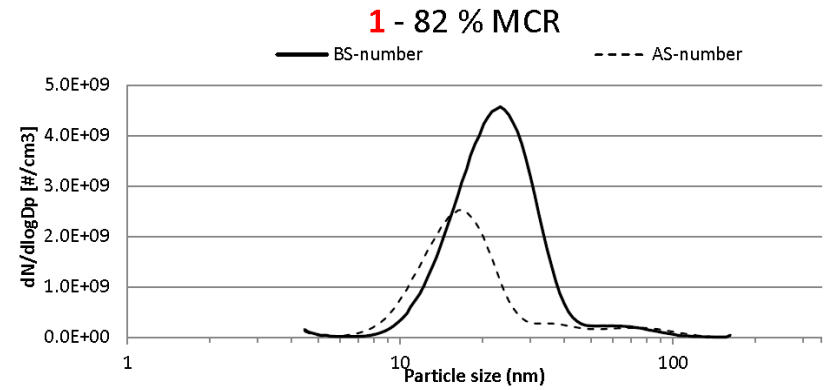

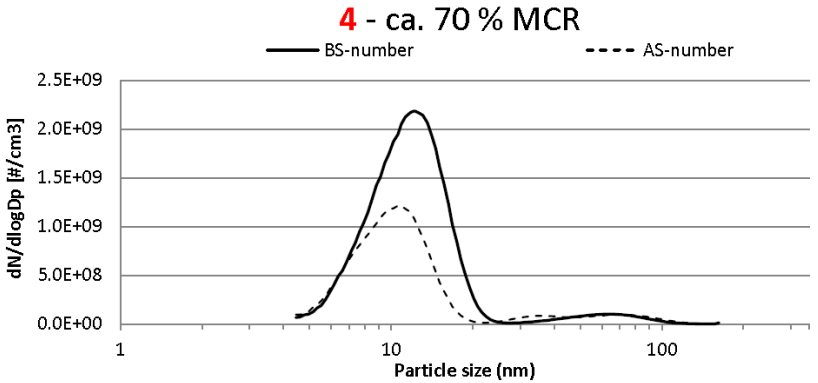

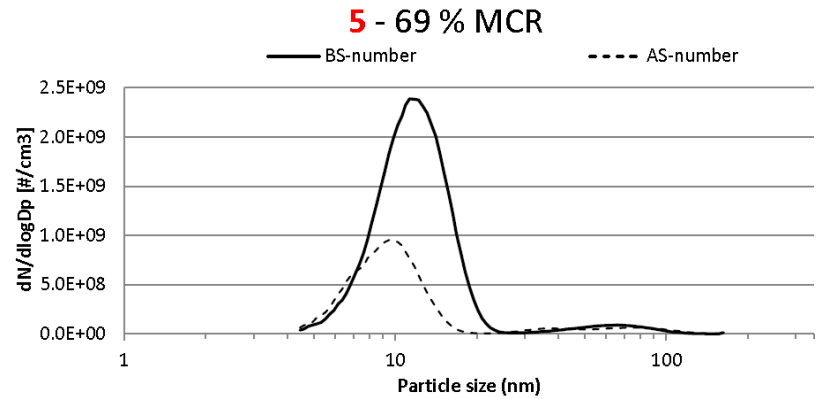

Focus period	Position BS/AS	MCR (average) [%]	Mean number conc. SMPS [x10^8 #/cm3]	PN reduction [%]
1	BS	81.8±1.1	16.9 ± 1.8	**46**
	AS	81.9±1.2	9.2 ± 0.4	
2	AS	82.2±1.0	9.3 ± 0.2	N.A.
3	AS	81.7±1.4	9.2 ± 0.2	N.A.
4	BS	73.1±2.5	7.7 ± 0.1	**41**
	AS	65.8±3.6	4.5 ± 0.2	
5	BS	69.1±1.0	7.8 ± 0.1	**58**
	AS	68.5±1.0	3.2 ± 0.1	

BS: Before scrubber, AS: After scrubber

PN reduction during focus periods

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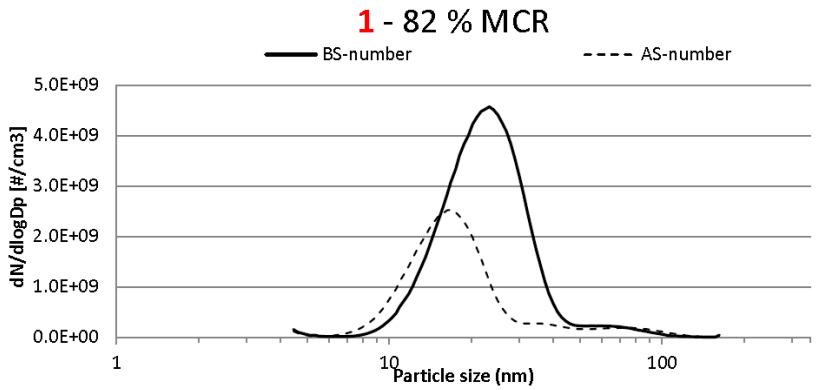

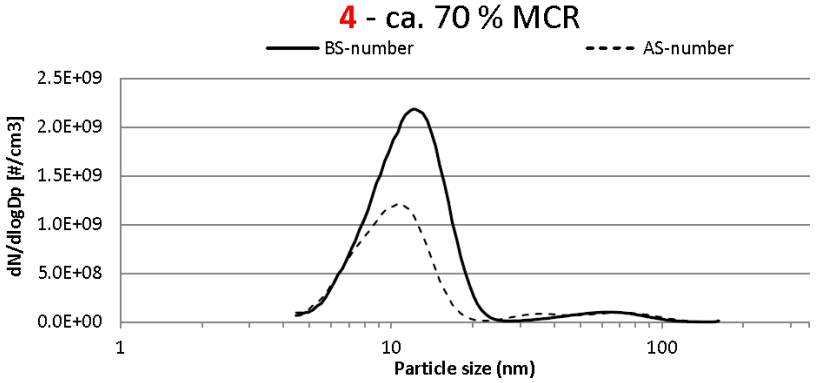

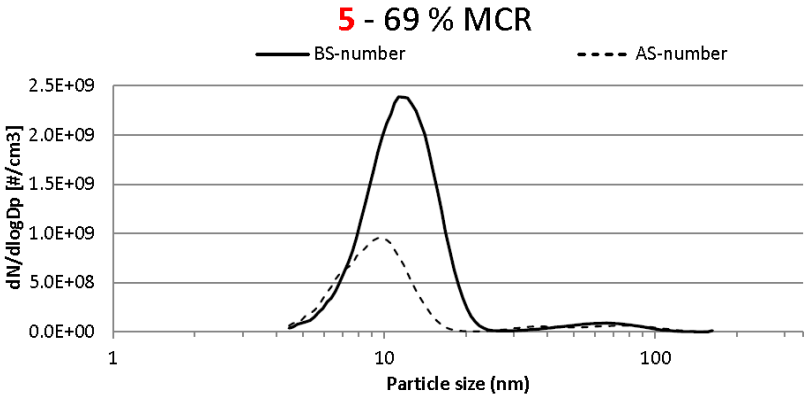

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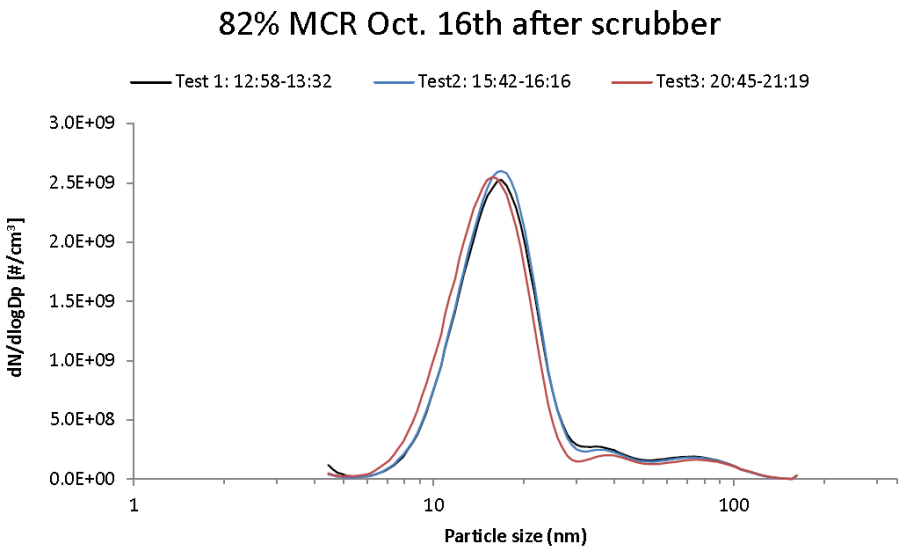
BS: Before scrubber, AS: After scrubber



PN comparison ELPI and SMPS

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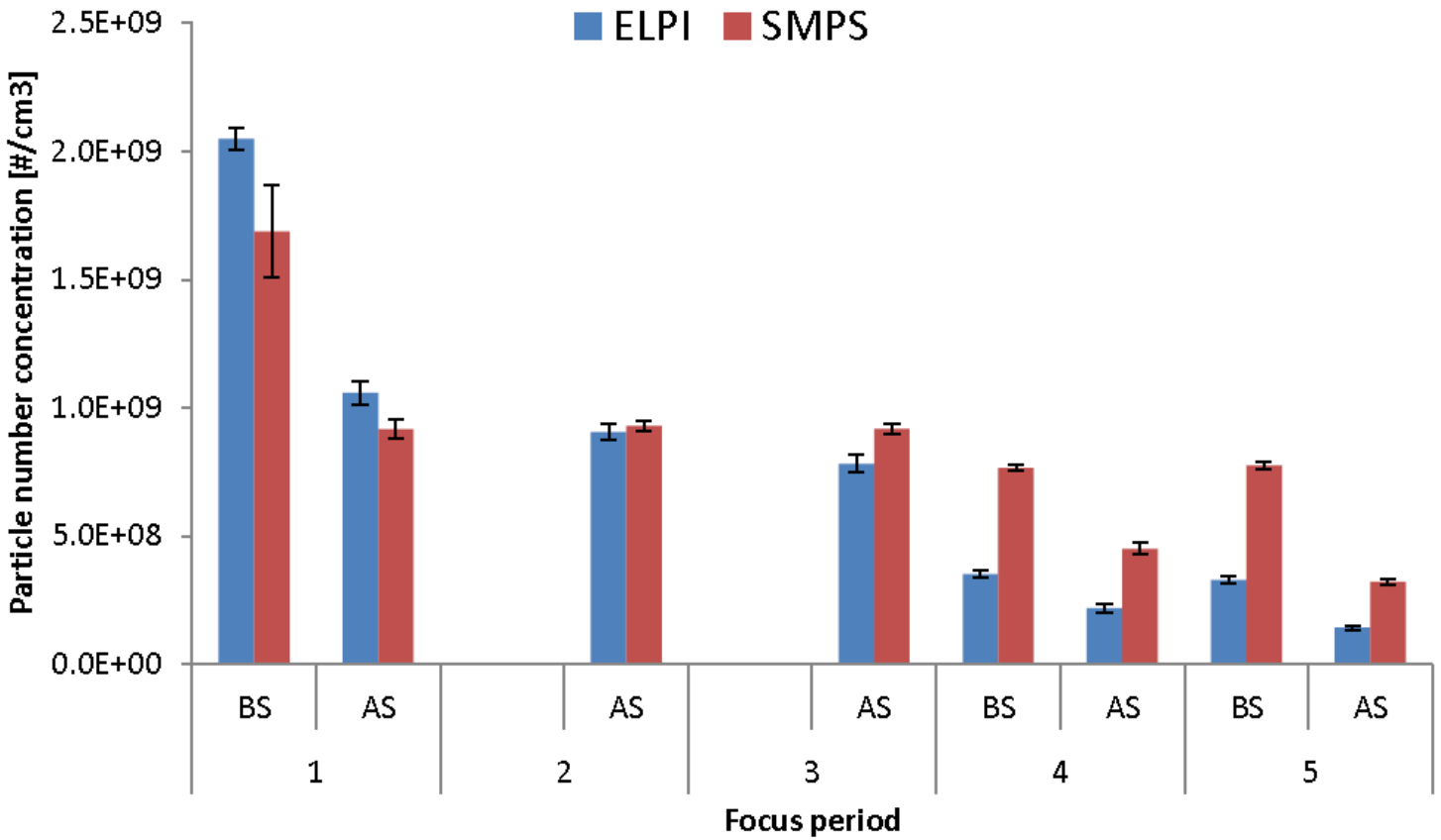

BS: Before scrubber, AS: After scrubber

PN comparison ELPI and SMPS

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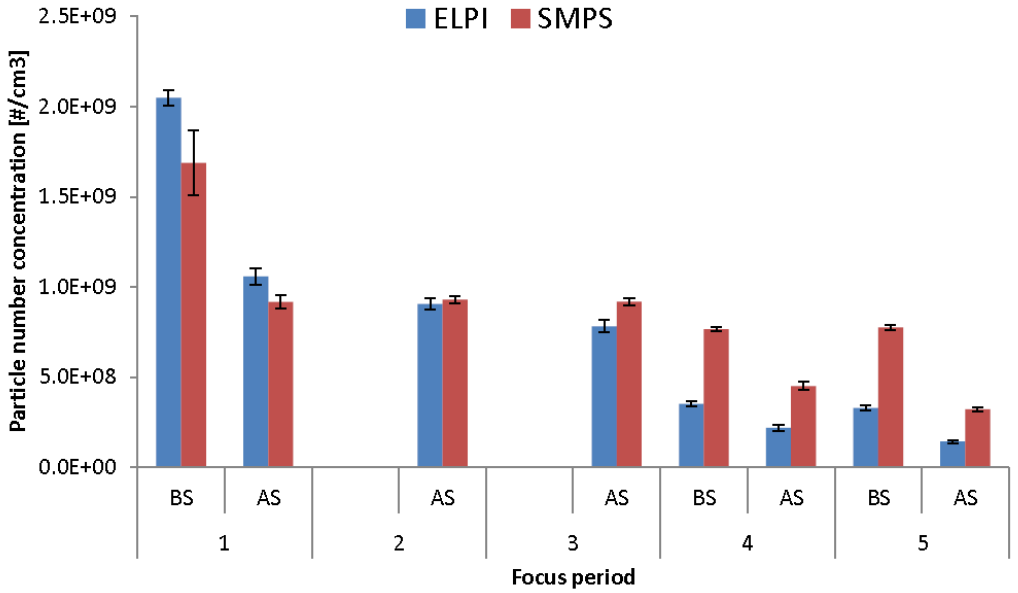

Focus period	Position BS/AS	MCR (average) [%]	Mean number conc. SMPS [x10^8 #/cm3]	Mean number conc. ELPI [x10^8 #/cm3]	PN reduction SMPS [%]	PN reduction ELPI [%]
1	BS	81.8±1.1	16.9 ± 1.8	20.5 ± 0.4	**46**	**48**
	AS	81.9±1.2	9.2 ± 0.4	10.6 ± 0.5		
2	AS	82.2±1.0	9.3 ± 0.2	9.2 ± 0.3	N.A.	N.A.
3	AS	81.7±1.4	9.2 ± 0.2	7.8 ± 0.3	N.A.	N.A.
4	BS	73.1±2.5	7.7 ± 0.1	3.5 ± 0.1	**41**	**38**
	AS	65.8±3.6	4.5 ± 0.2	2.2 ± 0.2		
5	BS	69.1±1.0	7.8 ± 0.1	3.3 ± 0.1	**58**	**57**
	AS	68.5±1.0	3.2 ± 0.1	1.4 ± 0.1		

Selected results from Feb. 2011

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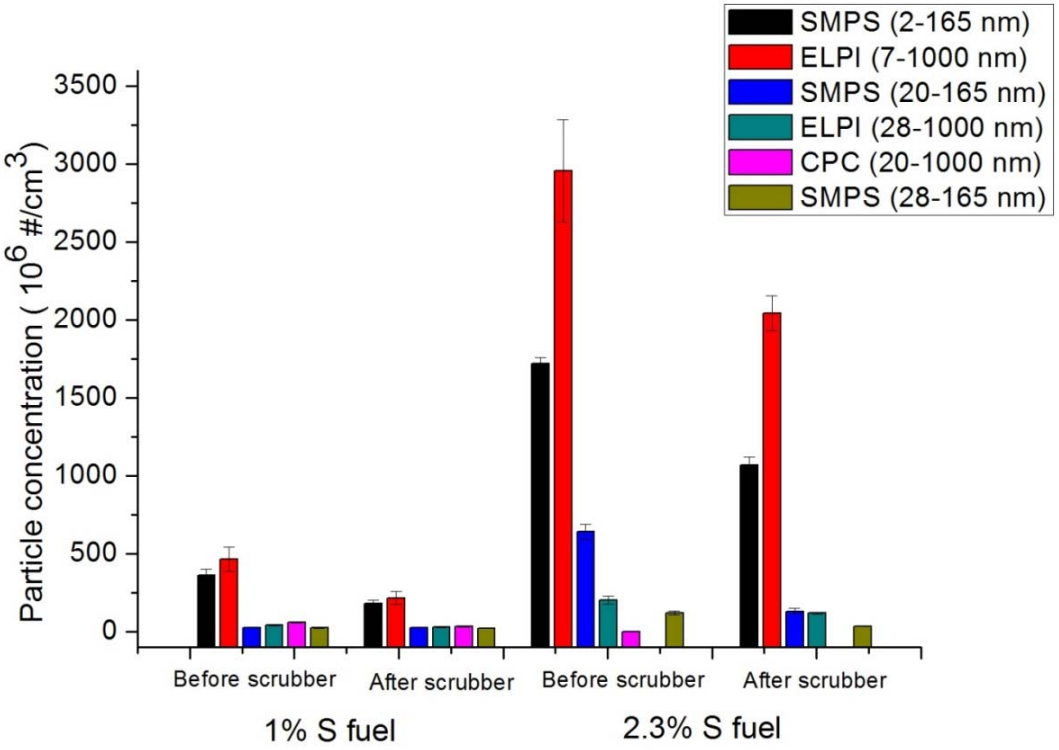

- When changing from 1.0 % S fuel to 2.3 % S fuel the particle number concentration for the specific operating conditions increases with a factor of 4.5-6.5

PSD comparison with Feb. 2011

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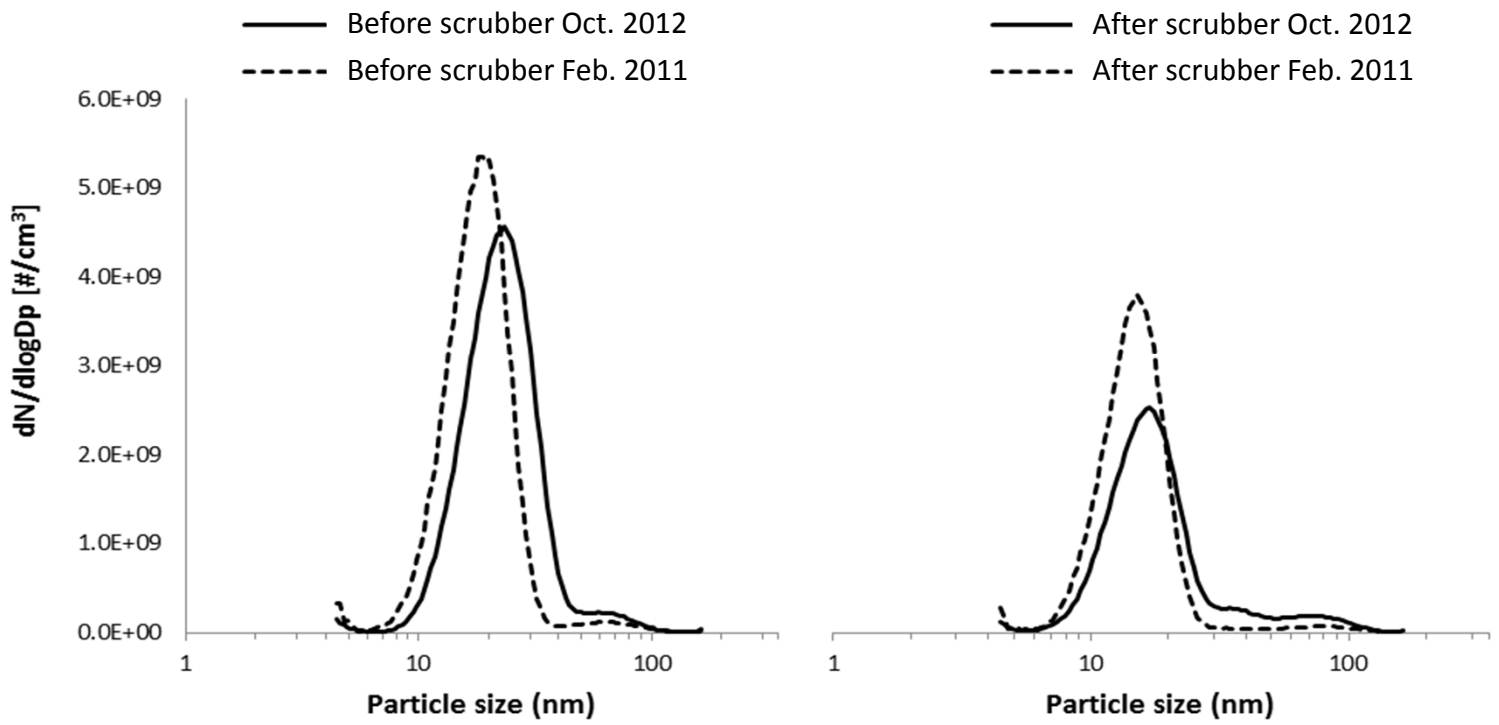

- Similar scrubber water and fuel consumption above
- Bimodal distribution before and trimodal after scrubber

Elemental analysis on ELPI stages

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	Before scrubber		After scrubber	
	Mass	% mass	Mass	% mass
C	711.2	67.9	372.6	48.1
N	30.8	2.9	0.0	0.0
O	169.2	16.2	202.3	26.1
Na	3.0	0.3	28.8	3.7
Mg	0.1	0.0	5.1	0.7
Al	0.0	0.0	0.0	0.0
Si	4.5	0.4	4.0	0.5
P	0.0	0.0	0.0	0.0
S	63.2	6.0	89.9	11.6
Cl	0.0	0.0	0.0	0.0
Sn	4.7	0.4	0.0	0.0
Ca	22.2	2.1	21.7	2.8
V	23.0	2.2	30.7	4.0
Mn	0.0	0.0	0.0	0.0
Fe	6.6	0.6	6.1	0.8
Ni	8.8	0.8	12.8	1.7
Cu	0.0	0.0	0.0	0.0
Zn	0.0	0.0	0.0	0.0
Total	1047.3	100.0	773.9	100.0

Summary of EDX analysis of the particulate material collected on the ELPI impactor stages < 3 µm.
Mass estimates given in mg/m3

Data from selected ~3-hour periods on day 1 before and after scrubber

Elemental analysis on ELPI stages

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	Before scrubber		After scrubber	
	Mass	% mass	Mass	% mass
C	711.2	67.9	372.6	48.1
N	30.8	2.9	0.0	0.0
O	169.2	16.2	202.3	26.1
Na	3.0	0.3	28.8	3.7
Mg	0.1	0.0	5.1	0.7
Al	0.0	0.0	0.0	0.0
Si	4.5	0.4	4.0	0.5
P	0.0	0.0	0.0	0.0
S	63.2	6.0	89.9	11.6
Cl	0.0	0.0	0.0	0.0
Sn	4.7	0.4	0.0	0.0
Ca	22.2	2.1	21.7	2.8
V	23.0	2.2	30.7	4.0
Mn	0.0	0.0	0.0	0.0
Fe	6.6	0.6	6.1	0.8
Ni	8.8	0.8	12.8	1.7
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Zn	0.0	0.0	0.0	0.0
Total	1047.3	100.0	773.9	100.0

Summary of EDX analysis of the particulate material collected on the ELPI impactor stages < 3 µm.
Mass estimates given in mg/m3

Data from selected ~3-hour periods on day 1 before and after scrubber

Trends:

- Carbon dominates PM
- No Cl detected
- Increase in mass fraction of Na, S, O, V, Ni after scrubber

Conclusion

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- Majority (number) of particles emitted before/after the scrubber are smaller than 30 nm.
- PN reduction by 35-60 % of the scrubber under the operating conditions of the selected focus periods.
- Good agreement between PN reductions calculated from SMPS and ELPI data
- Good agreement with measurements carried out in Feb. 2011 (for comparable engine and scrubber conditions)

Acknowledgements

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- DFDS Seaways
- FORCE Technology
- University of Copenhagen
- Financial support from the Danish Agency for Science, Technology and Innovation