Characterization of particle emissions from a marine diesel engine: Influence of sampling temperature on particle number, size, and morphology

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Introduction

Along with the reduction of particle emissions from on-road engines, an increasing focus is turned towards particle emissions from marine diesel engines. Particle emissions from diesel engines are traditionally regulated according to the emitted particle mass. However, EU emission regulation for land-based diesel vehicles will from 2015 also include standards for the emitted number of particles. Compliance measurement systems for particle number emissions have been recommended for on-road diesel vehicles (Anderson et al., 2010). The recommended systems include a sampling system involving thermo-evaporation in order to remove volatile material before measuring the total particle number. In this study, the effect of thermo-evaporation on the measured particle number, size and on the morphology of the particles emitted from a ship engine was investigated. The engine studied was a 7 MW MAN two-stroke marine engine, and the fuel used was gasoil containing 0.002 % w/w sulfur.

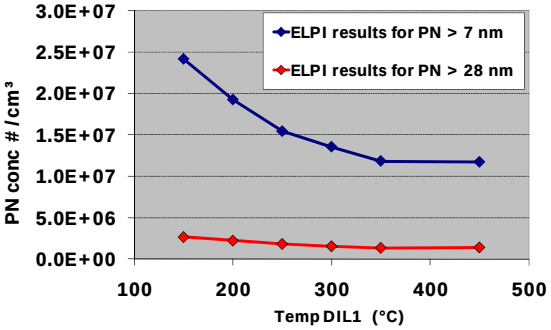
Methodology

The particle number concentration in the engine exhaust at 50% engine load was measured by an ELPI (Electrical Low Pressure Impactor). The sampling system included dual ejector diluters. The temperature of the first diluter was increased in steps from 150 °C to 450 °C. Size distributions were studied by both ELPI and SMPS (Scanning Mobility Particle Sizer). Impactor samples were collected in separate, 3-4 hour tests at 150 °C and 350 °C, respectively, and these were examined by AFM (Atomic Force Microscopy) and SEM (Scanning Electron Microscopy).

Results and discussion

The results of particle numbers measured during increasing sample temperature are shown in figure 1. At increasing sampling temperature, small, condensed oil droplets will evaporate. This explains the reduced particle numbers found at increasing temperatures in figure 1.

Figure 1. Number of particles from a marine diesel engine measured during increasing temperature in sample hose and the first diluter. Measurement performed by means of ELPI.



An example of size distributions measured by SMPS and ELPI in parallel during sample heating to 350 °C is shown in Figure 2a and 2b. A good agreement between the measured size distributions with SMPS and ELPI is found. The total PN concentration increases significantly when the engine auxiliary blower is turned on, and

furthermore it seems that when the engine auxiliary blower is switched on, the particulate size distribution changes from unimodal distribution to bimodal.

Figure 2. Size distributions measured by means of SMPS (2a) and ELPI (2b) during 50 % engine load with the engine auxiliary blower on and off, respectively. Sample system temperature: 350 °C.

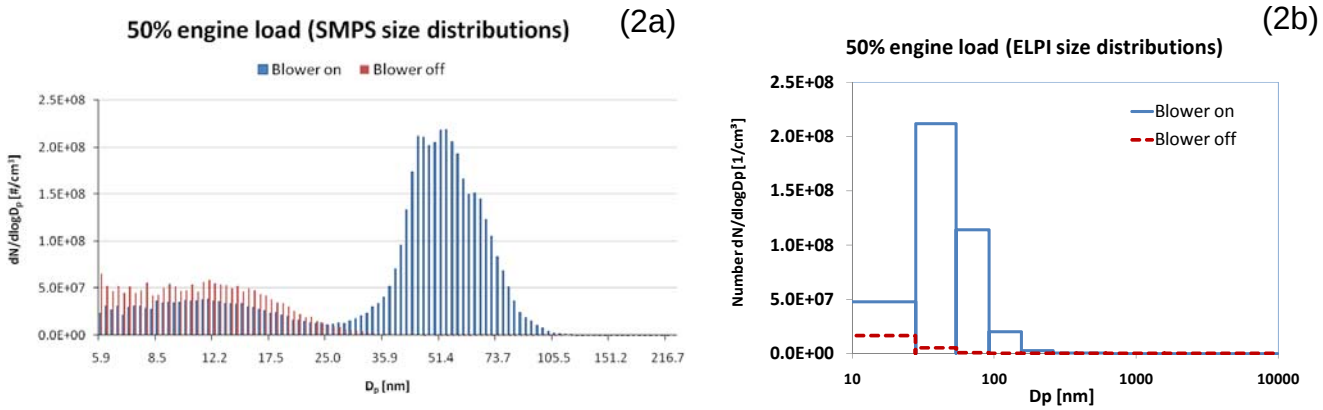
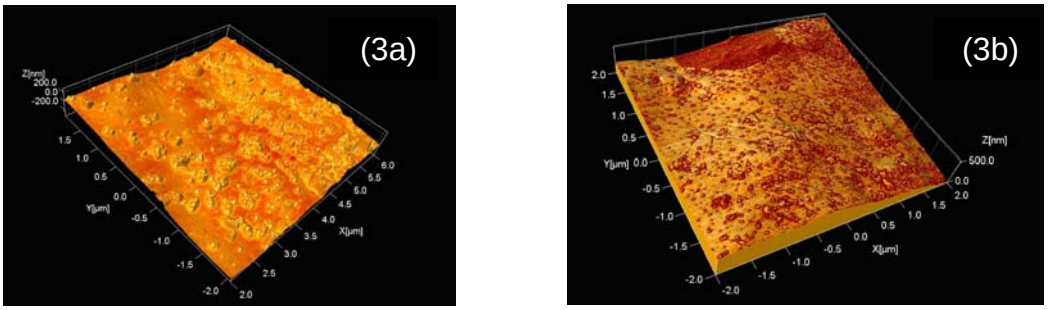


Figure 2a illustrates the clear shift to smaller particle diameters, when the auxiliary blower is turned off. Both in figure 2a and figure 2b, the maximum peak mode shifts from about 50-60 nm to less than 20 nm when the auxiliary blower is turned off. A new category of particulates seems to be generated, when the blower is turned on. These 50-60 nm sized particles may occur due to accumulated cylinder lubrication oil rests around the blower, being mixed with the scavenge air as the blower starts/is running. The purpose of the auxiliary blowers on a two-stroke marine engine is to supply the engine with sufficient combustion air at low engine loads where the turbocharger has a low efficiency. Without the auxiliary blower the deteriorated combustion will result in visible smoke, increased fuel oil consumption and detrimental high heat load of the combustion chamber parts.

Figure 3a and 3b shows images from the AFM analysis for particles collected by means of ELPI during 3-4 hours periods with sample heating to 150 °C and 350 °C, respectively. These samples were collected during varying engine loads.

Figure 3. AFM image of particles sampled at 150 °C (3a) and at 350 °C (3b).



In figure 3, the color shading superimposed on the topography shows the local phase signal measured by the AFM. A color contrast in the phase signal indicates a change of the interaction conditions between the oscillating AFM tip and the sample surface. These changes are typically caused by variations in the material properties such as viscoelasticity, friction or hardness. In figure 3a, the superimposed phase signal shows for each particle a brighter topographic centre surrounded by darker material. This indicates that the centre material of a particle has different material properties as the surrounding layer. It is therefore likely that the particles found in the 150 °C sample contained one or more central cores surrounded by a shell with different material properties. In figure 3b, the colors representing the phase contrast are more uniform within the topography of individual particles, indicating that the majority of particles sampled at 350 °C do not have varying material properties. Both the reduced number concentrations and sizes at higher sampling temperatures and the decreased amount of shell material can be explained by the effect of thermo-evaporation on semi-volatile particles, i.e. residuals of un-combusted hydrocarbons arising from e.g. fuel and lubrication oil. The AFM results in figure 3b support the assumption that most of the particles' surface layer of volatile compounds has evaporated in the 350 °C sample system, leaving mainly solid particles in the sample.

The results show that it is important to control the sampling temperature when sampling particles from marine diesel engines. As for land-based diesel engine test protocols, the results presented here indicate that test procedures for marine diesel engines become more robust and reproducible when the sampling system includes a thermo-evaporation at 350 °C.

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Anderson, J. et al. (2010). Particle Measurement Programme (PMP). Heavy-duty Inter-laboratory Correlation Exercise (ILCE_HD) Final Report.

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Influence of sampling temperature on particle number, size, and morphology

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Particle number (PN) measurements in exhaust from marine diesel engines?

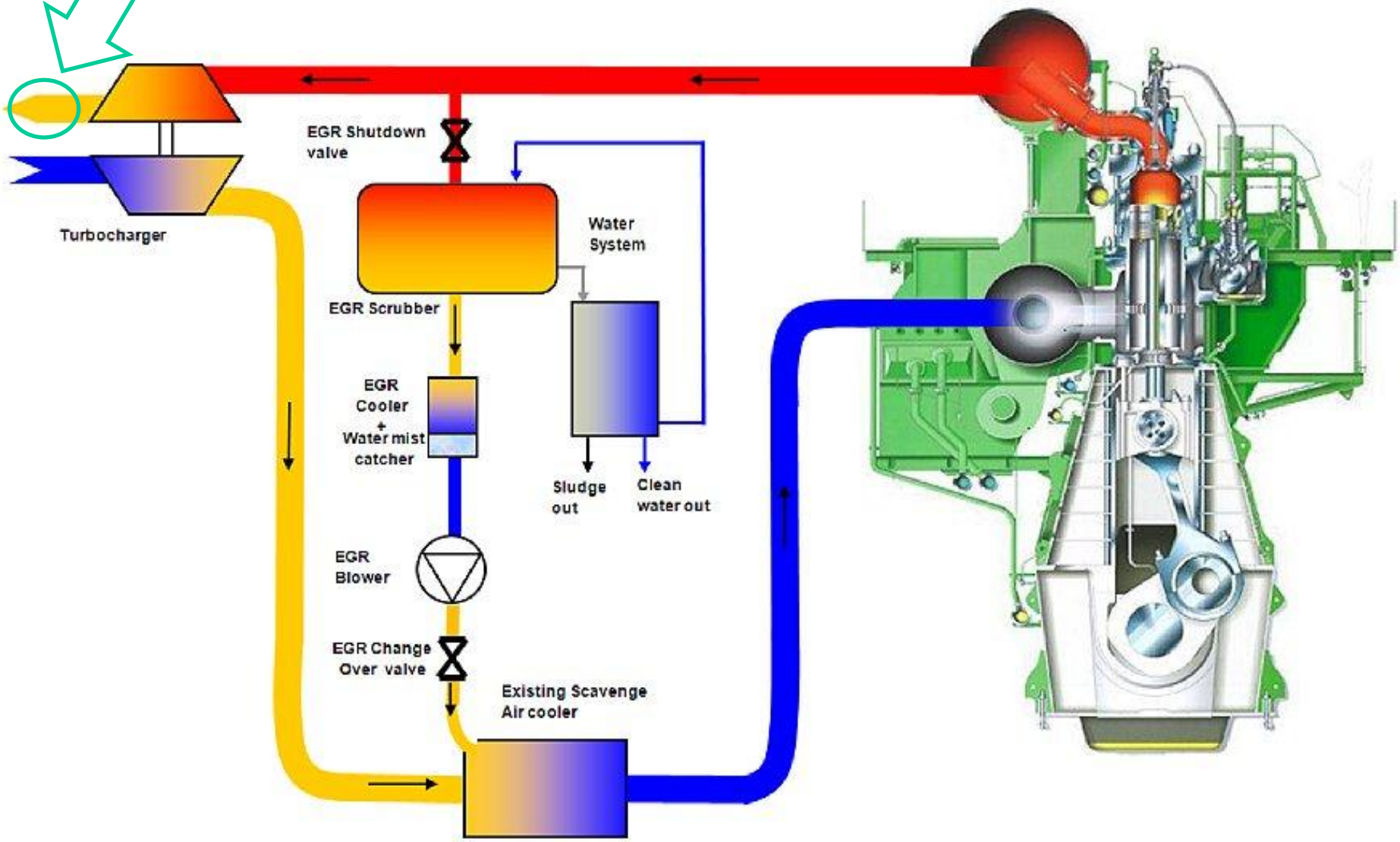
- For land-use diesel vehicle emissions, PN is measured according to the PMP (UNECE WP29/GRPE group).
- The PMP recommends that particle number measurements in diesel vehicle exhaust gas should include a selected size range only (dia. > 23 nm).
- The PMP procedure has been designed to count solid particles only, and to eliminate volatile particles.
- The latest PMP report recommends a treatment of the sample gas in a thermo-evaporation unit, heated to 350 °C.

Objective

1. To investigate the effect of thermoevaporation on PN measurements in exhaust from a two-stroke marine engine.
2. To compare ELPI and SMPS measurement results during different engine conditions.

MAN Diesel & Turbo test engine

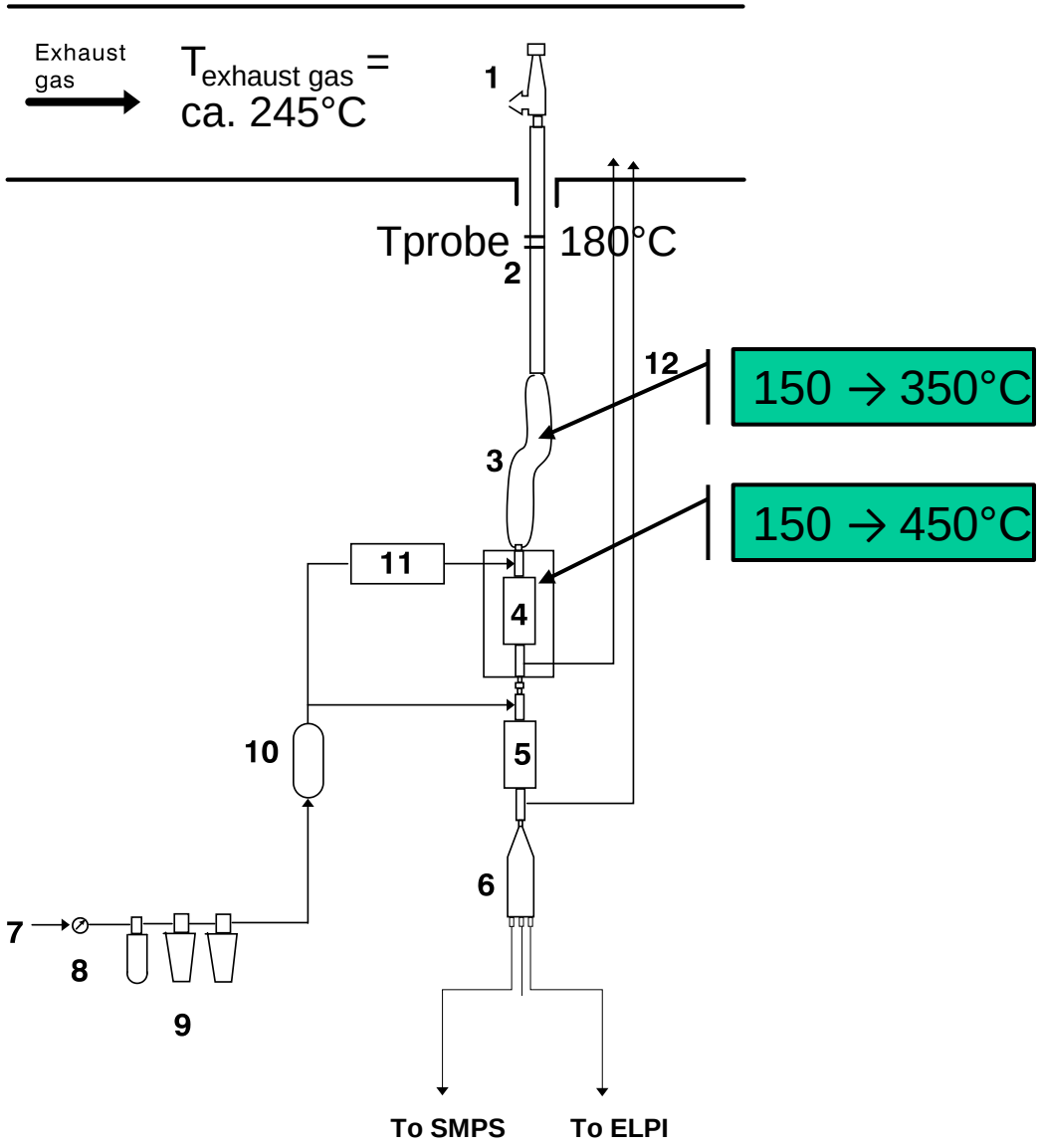
Measurement location



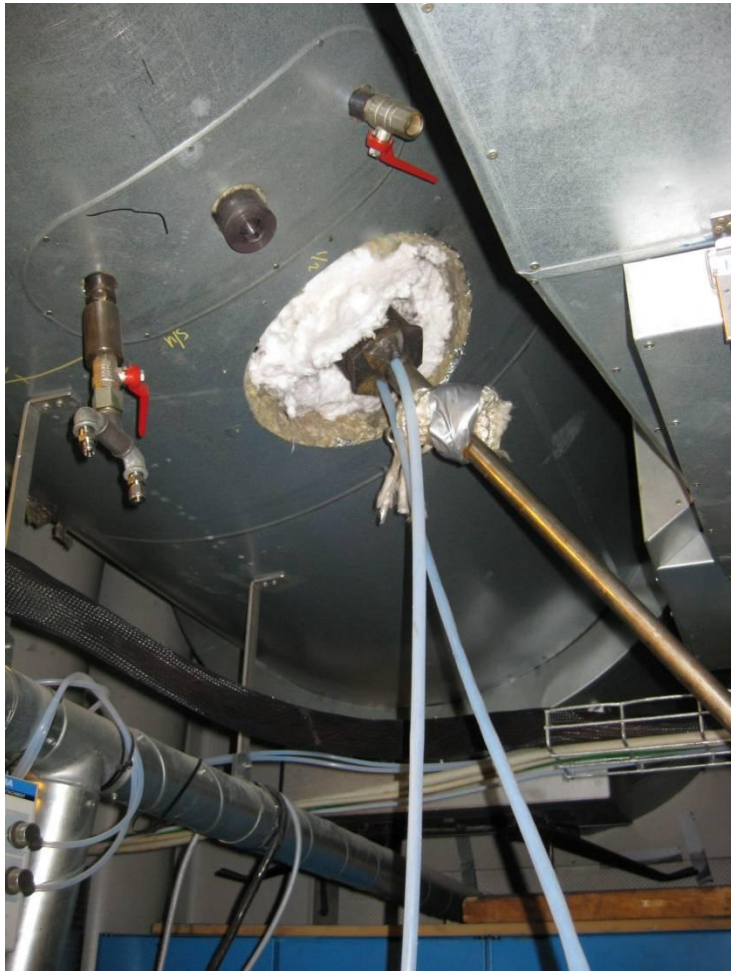
Engine specifications

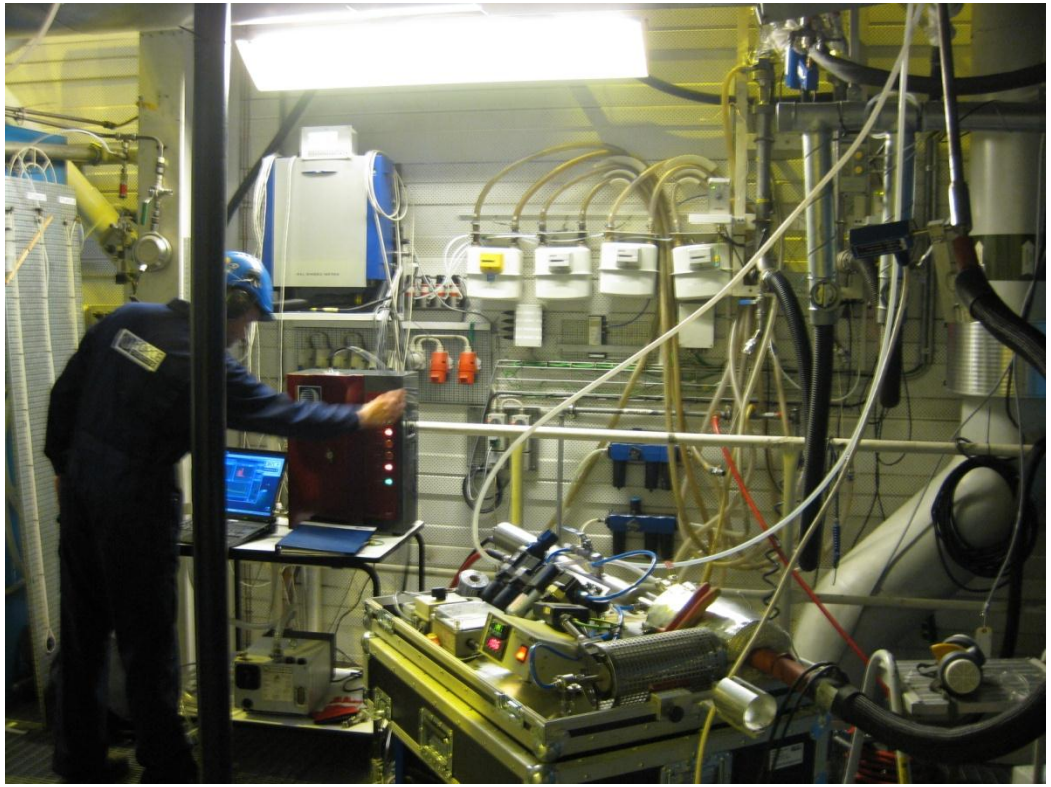
Specification of MAN B&W 4T50ME-X	
Power	7080 kW
MEP	20 bar
Speed	123 rpm
Number of cylinders	4
Bore	500 mm
Stroke	2200 mm
Fuel	MGO (0.002 % w/w S)

Sample setup (1)

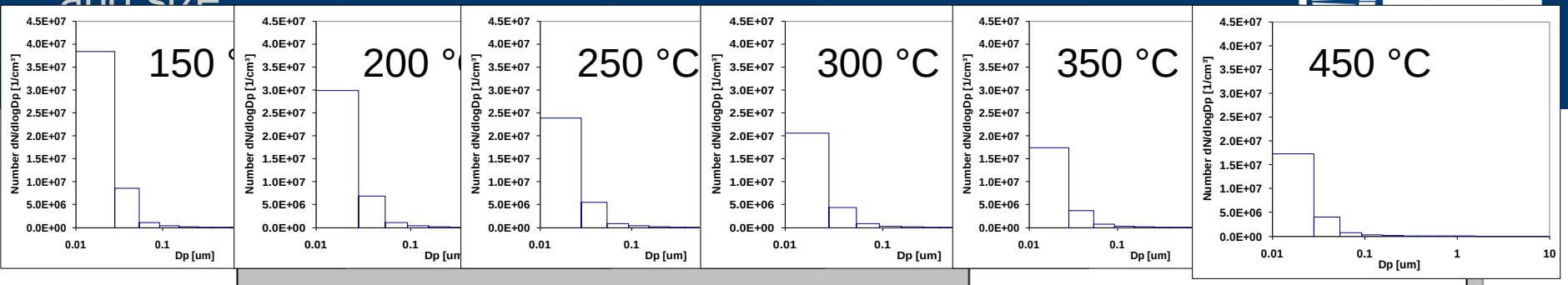


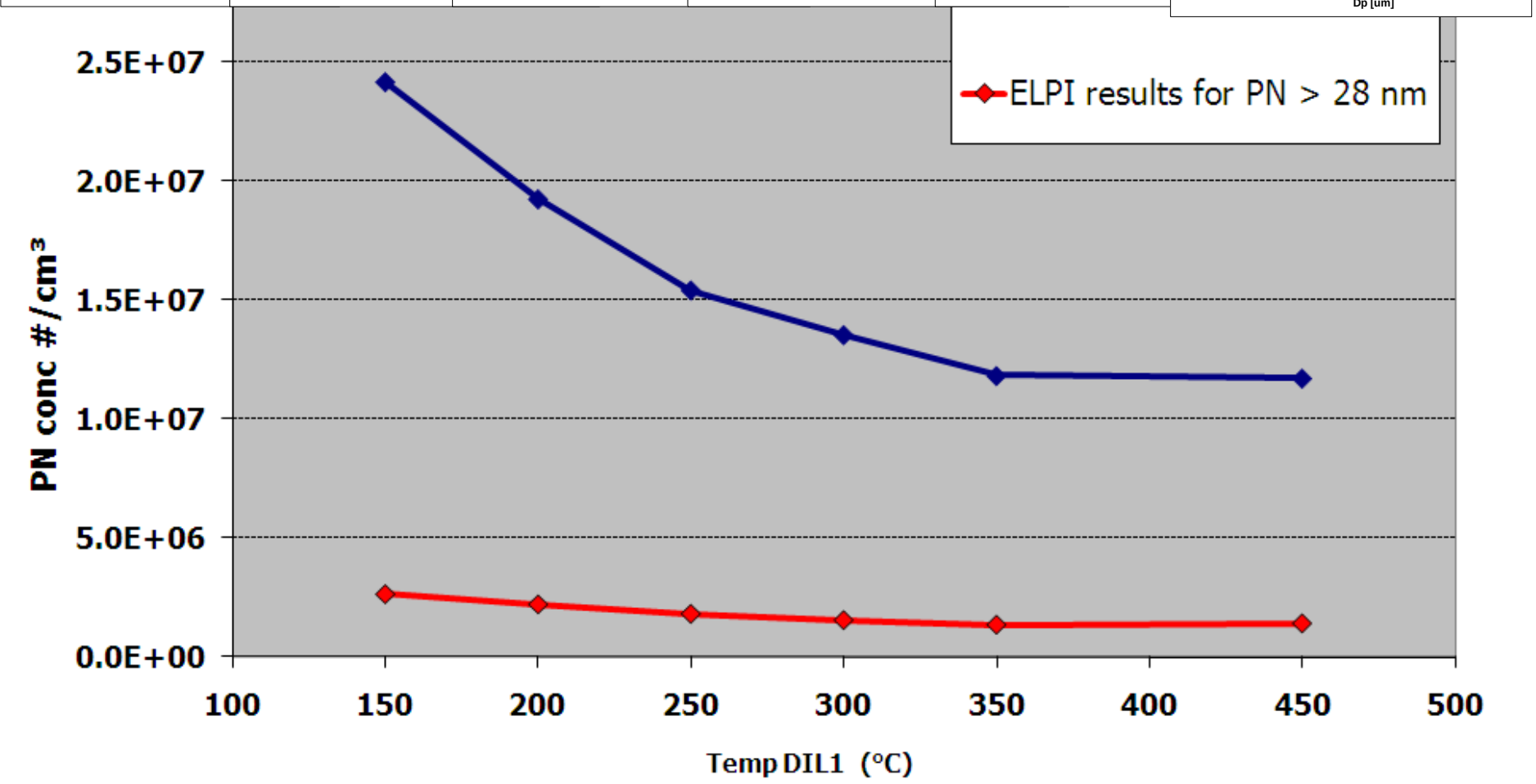
Sample setup (2)





1A. Effect of thermo-evaporation on particle number and size



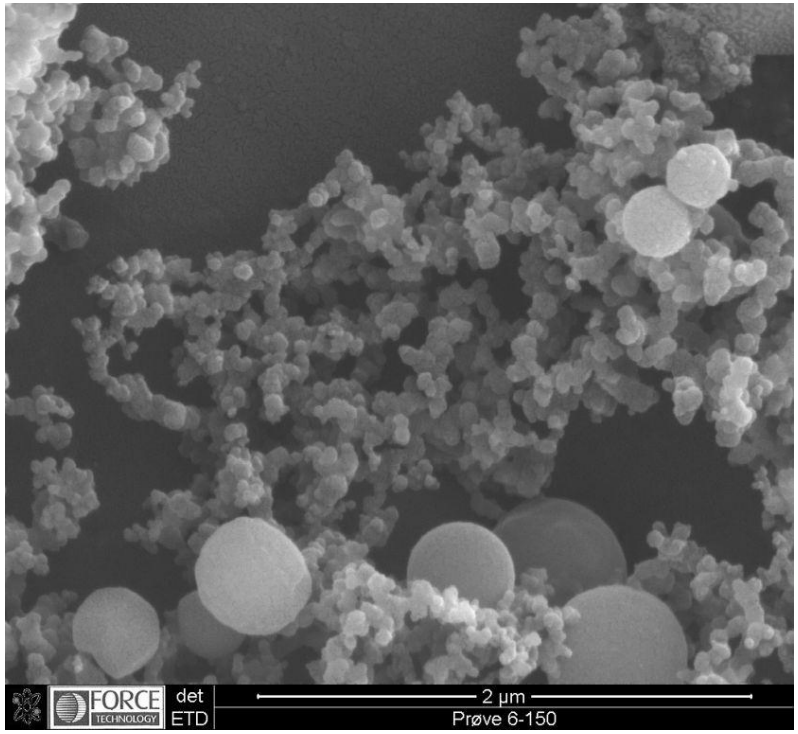


2A. Analysis of effect of thermo-evaporation on morphology

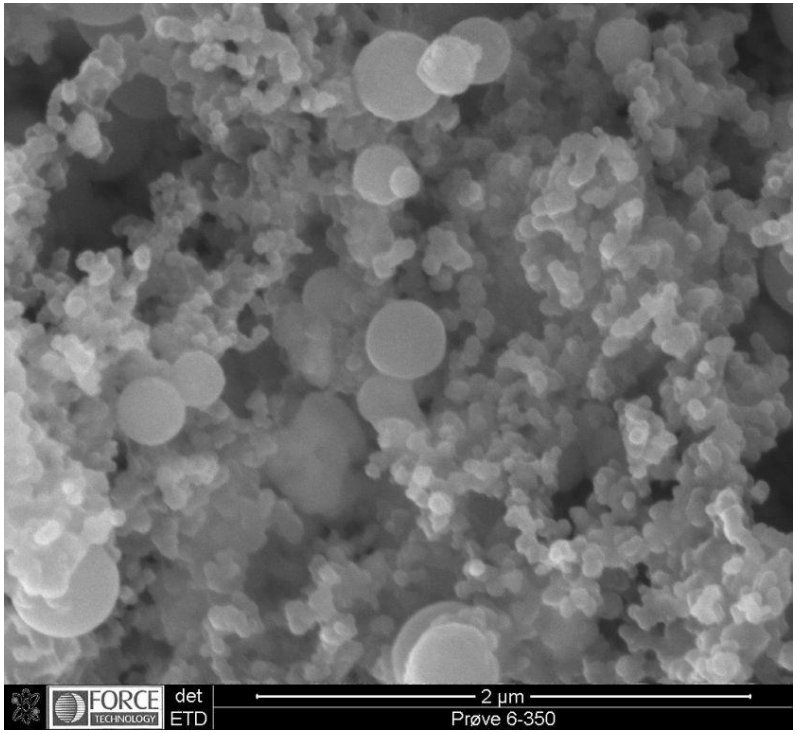
- Analysis of ELPI impactor samples from
  - 3 hours measurement with ELPI at sample system heated to 150 °C
  - 3 hours measurement with ELPI at sample system heated to 350 °C

Morphology: 150 °C vs. 350 °C sampling
SEM analysis

35%-75% load,
Sampling at 150 °C, 23 aug. 11-14
ELPI stage 6 (380-610 nm aerodyn dia)

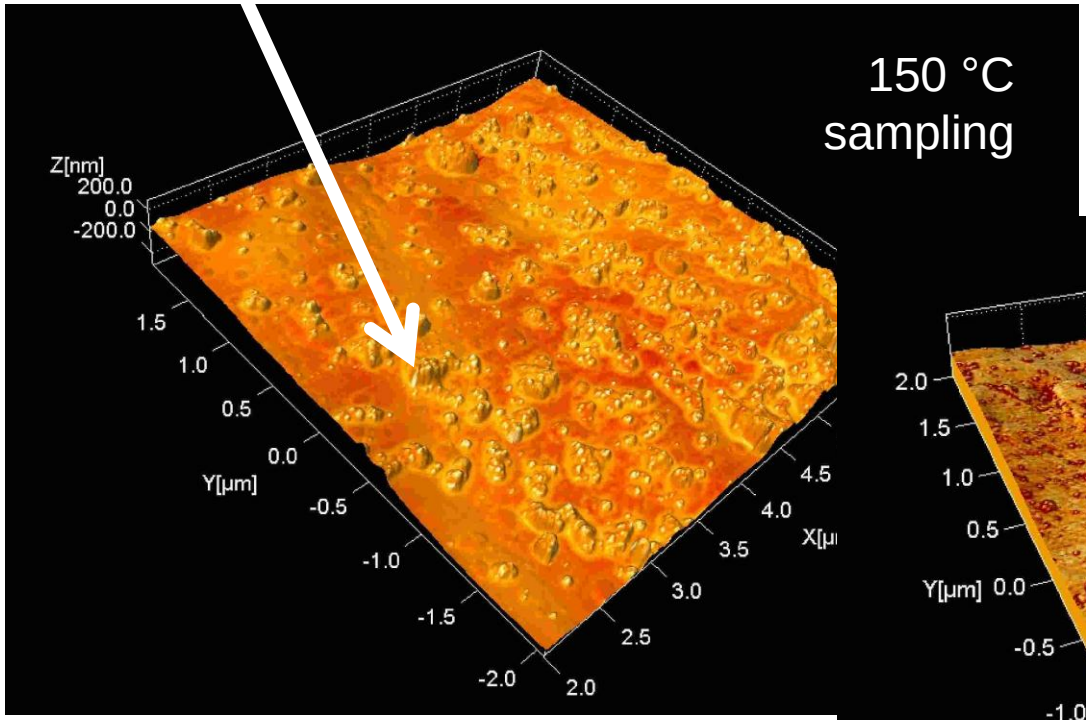


75% load,
Sampling at 350 °C, 23 aug. 14-16
ELPI stage 6



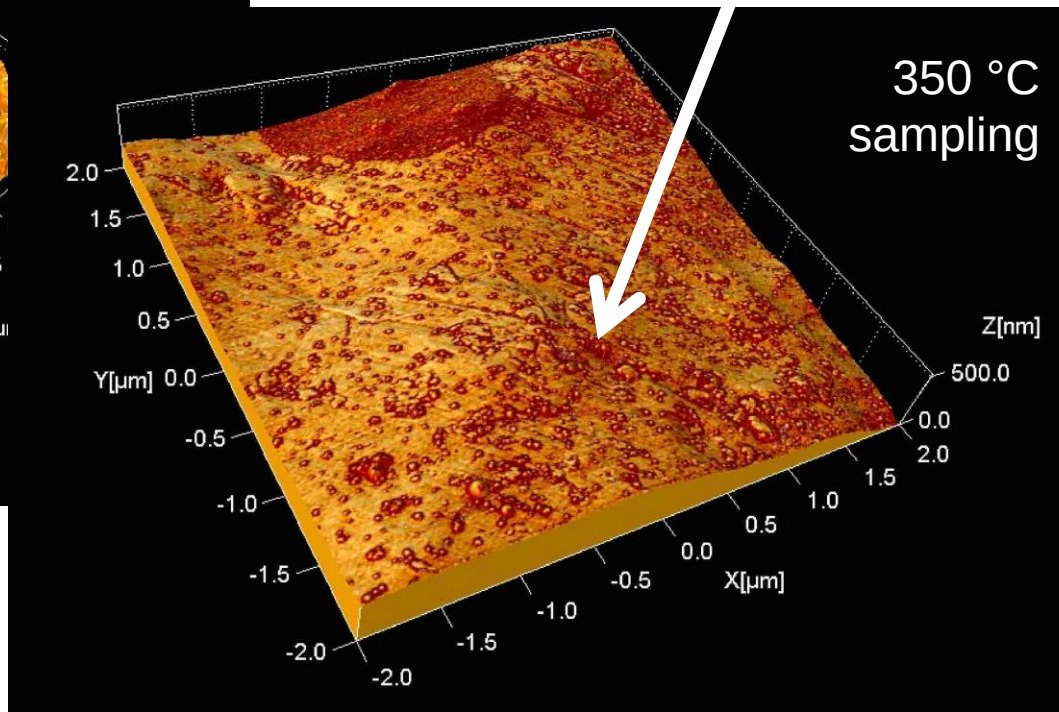
Analysis of particle material properties by AFM (Atomic Force Microscopy): 150 °C vs. 350 °C sampling

Most of the particles show a systematic variation of coloring (phase contrast) within their topographic centres: This indicates that the particle consists of material with different properties.

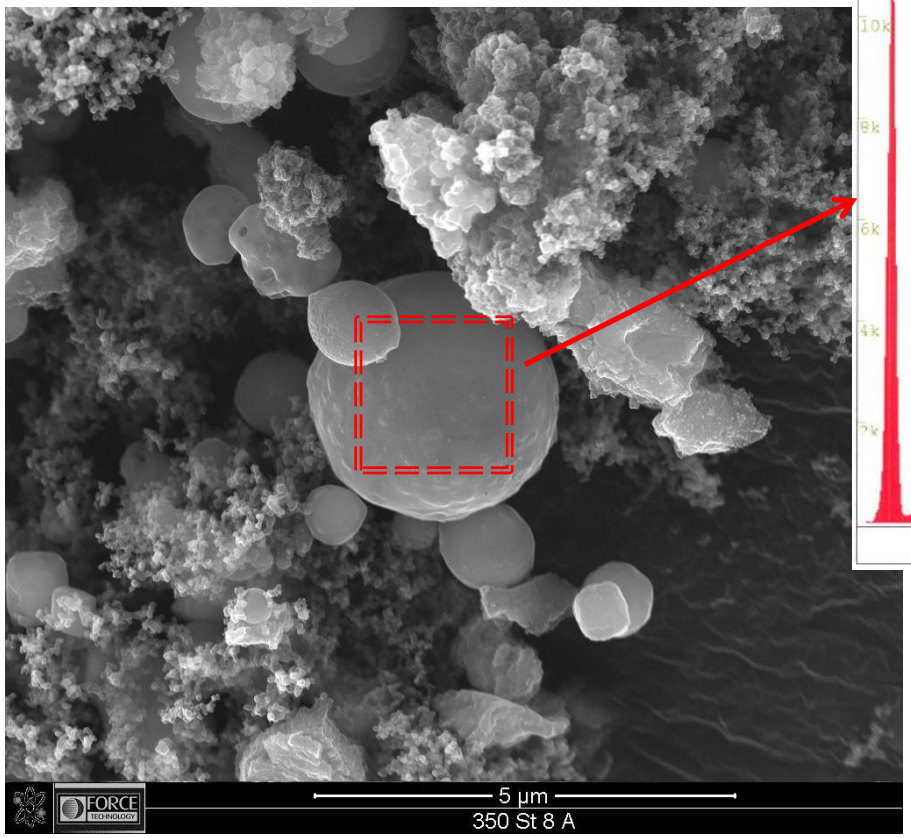


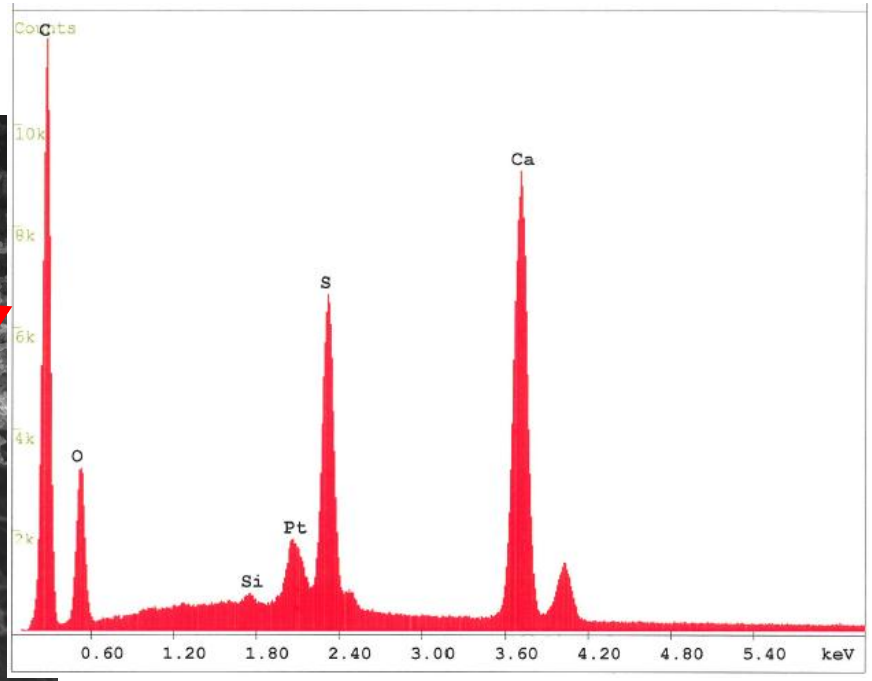
Such properties would be expected from a particle core embedded in a softer material (e.g. semivolatiles).

Most of the particles have a uniform central color shading.



Large spherical particles
Elemental analysis by EDX



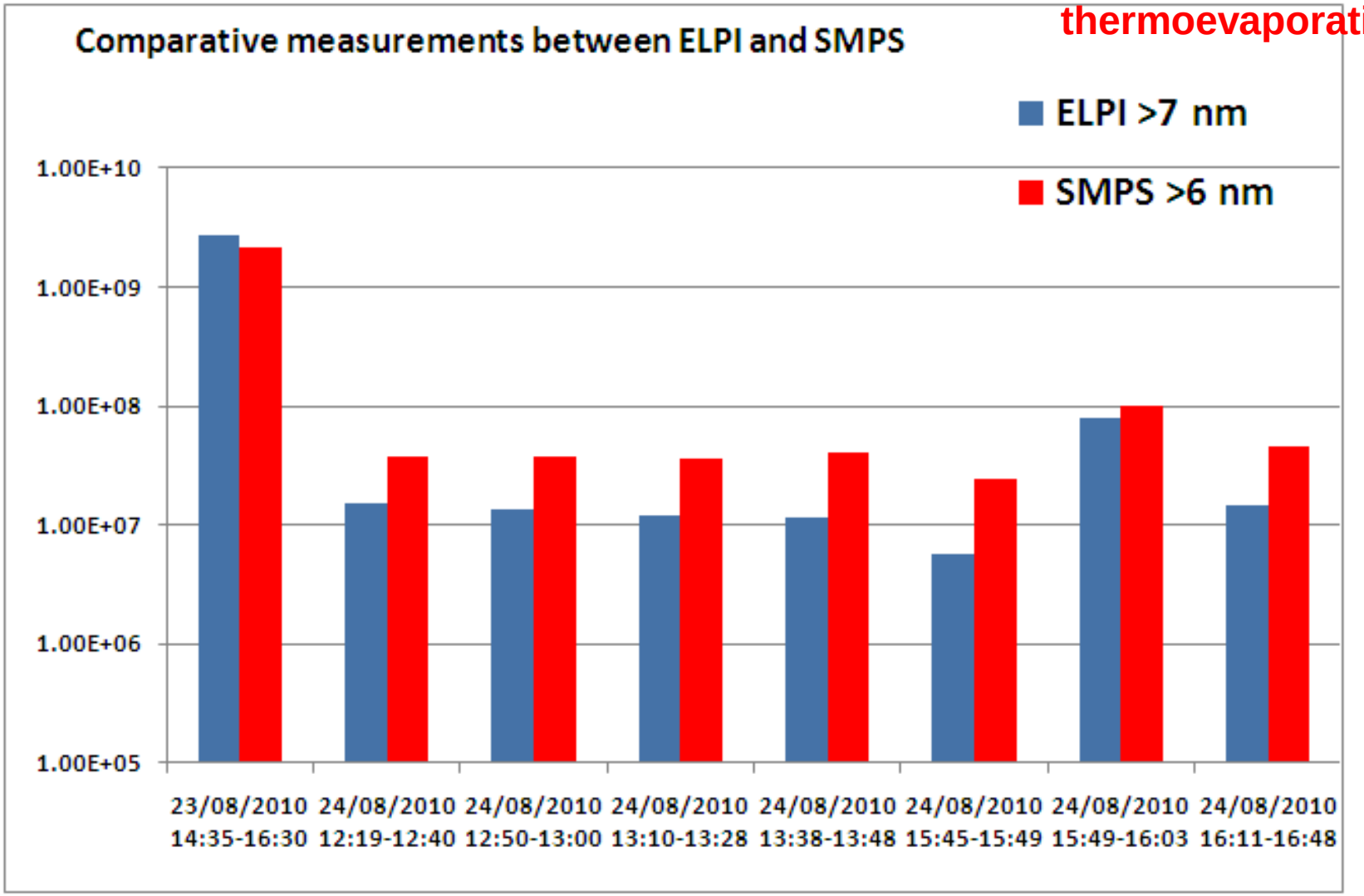


Sample A: ELPI St 8
d_a=[2400-4000] nm

Source of large particles?
Not Cat Fines (no high amount of Al/Si)!
Ca/S content indicates lube oil

Comparative measurements: ELPI and SMPS

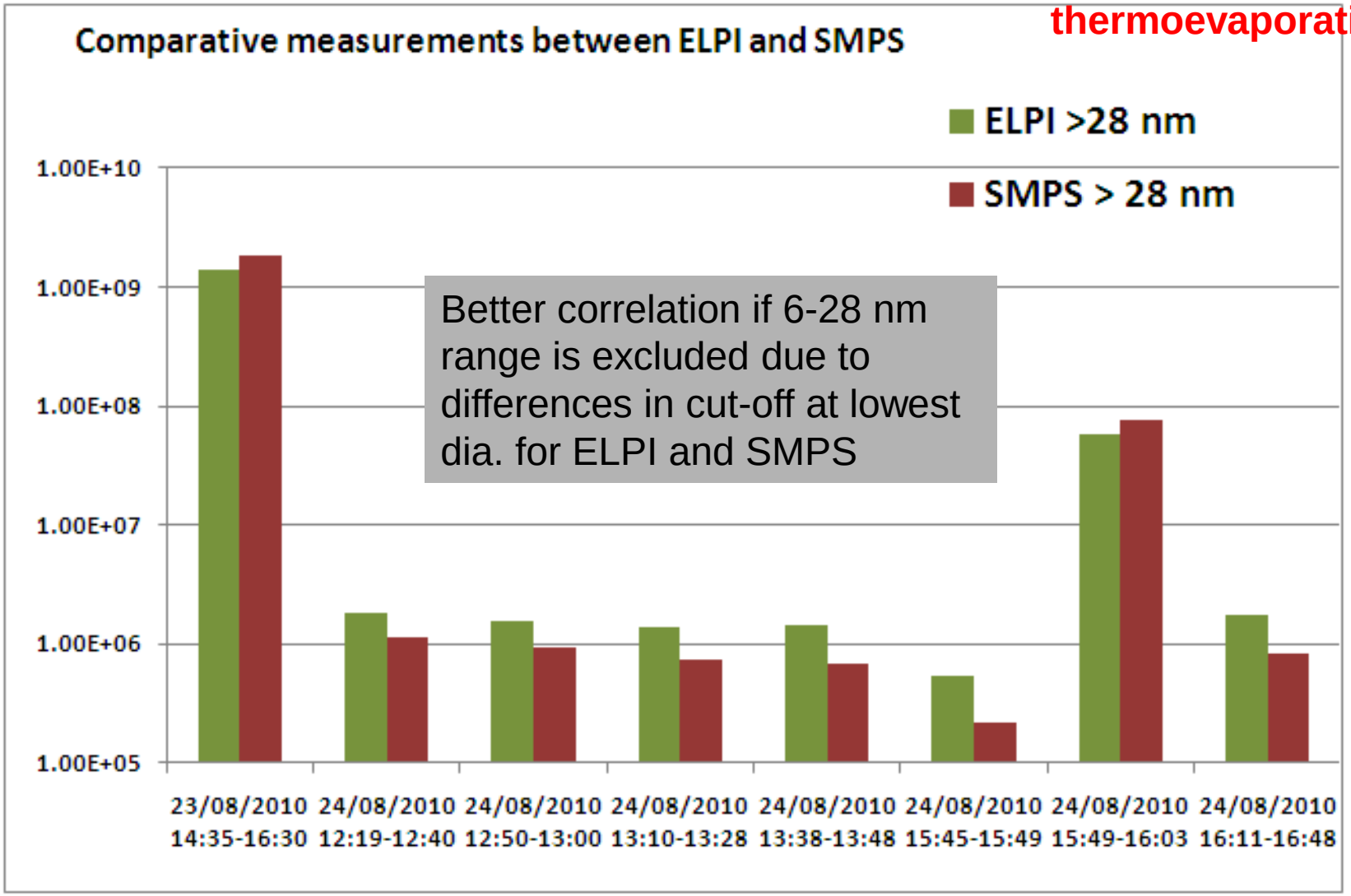
350 °C thermoevaporation.



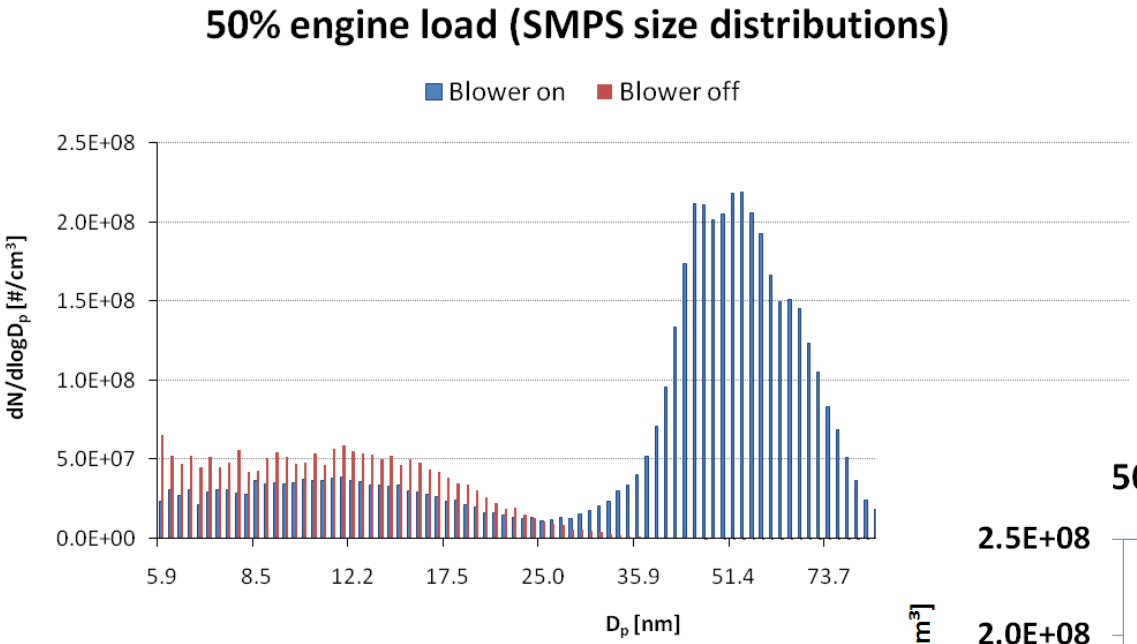
Comparative measurements: ELPI and SMPS

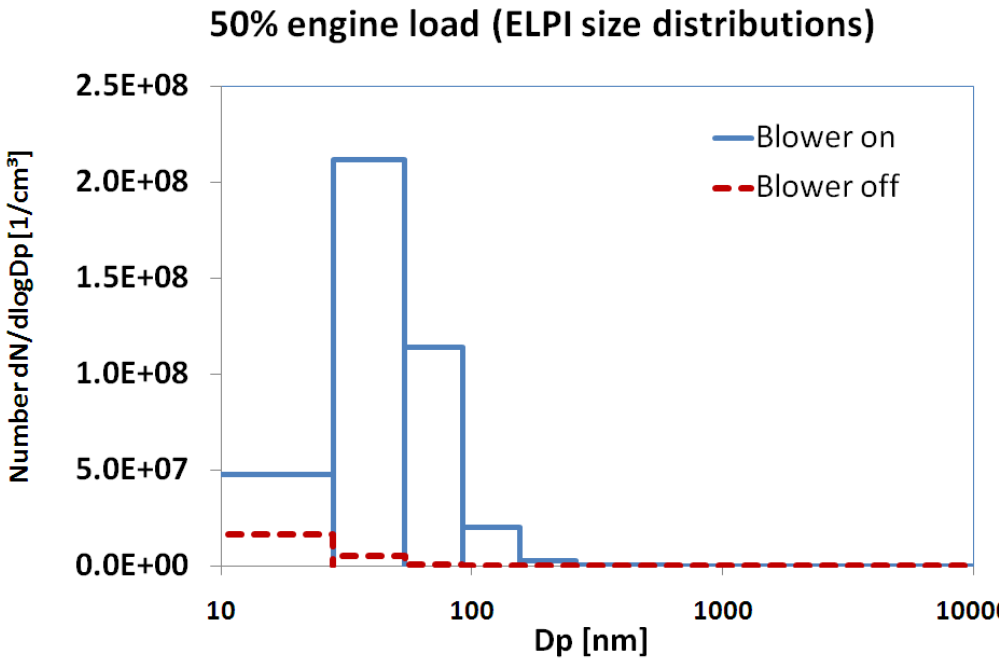
6-28 nm dia. **excluded**

350 °C thermoevaporation.



Size distributions measured with engine blower on/off





Conclusion: Thermo-evaporation

- When the sampling system's temperature was increased from 150°C to 350°C, the evaporation of semivolatiles caused a significant reduction in both the particle size and number.
- Areas measured by AFM on the 150°C sample contained particles that displayed a color signature equivalent to a particle core embedded in an outer shell of different properties (e.g. semi-volatiles). The same indication of embedded particle cores was not found in the areas scanned by AFM on the 350 °C samples.

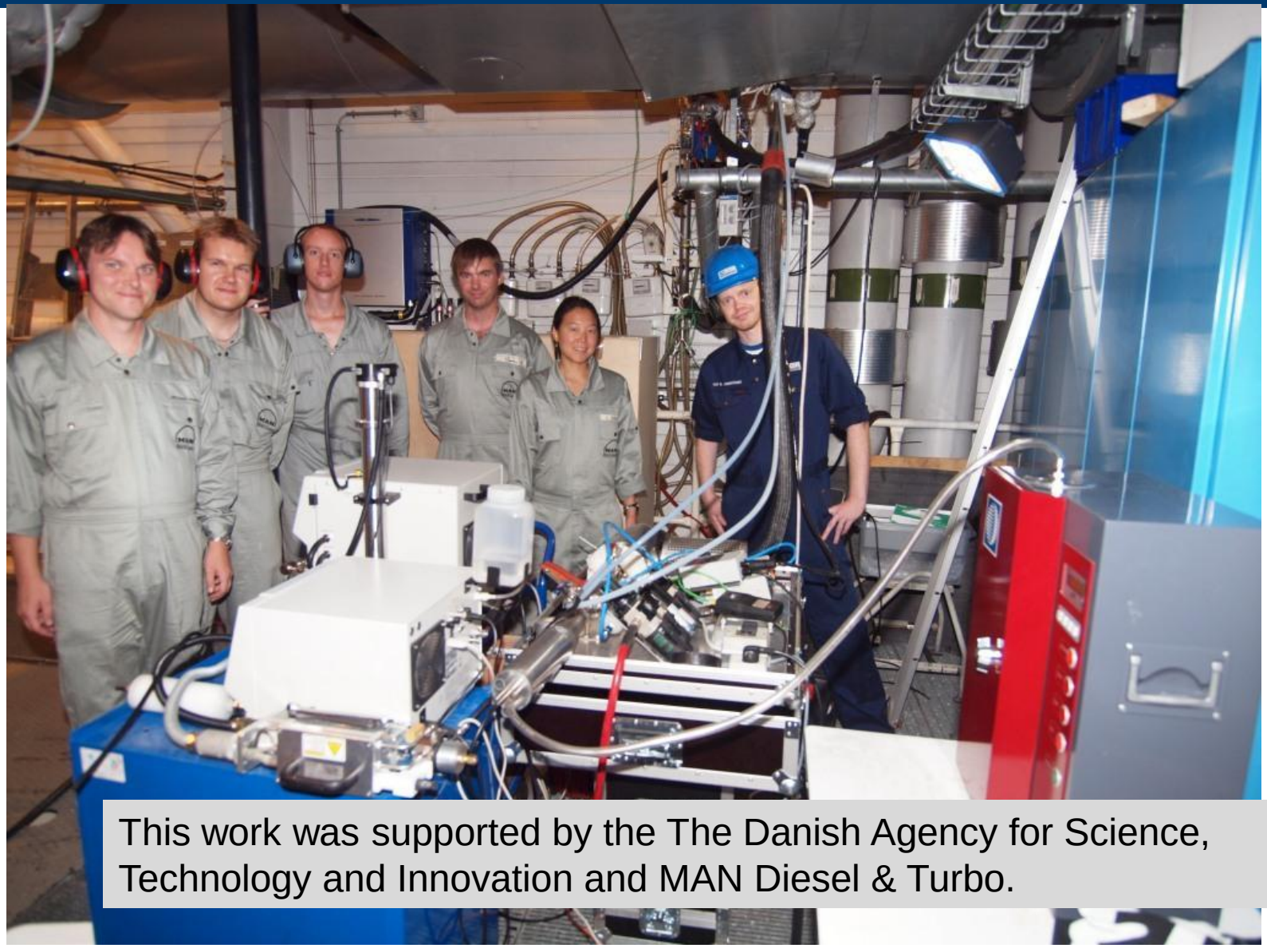
Conclusion: Comparison of ELPI - SMPS

- Good agreement in spite of different equivalent diameters used
- Highest difference is seen for diameters< 28 nm, where the effects of differences in measurement principles and cut size are strong.

Final remark

- The effect of sample temperature is strong for PN measurements on two-stroke ship engines, where relatively high of amounts lubrication oil may occur.
- Thermo-evaporation to 350 °C (as recommended for land-use diesel vehicle emission), is important to maintain reproducible results.

Thank you for your attention!



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