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Influence of sampling conditions, engine load and fuel quality on measurement of ultrafine particles from a modern Diesel vehicle
Part 1: sampling-measuring- and analyzing methods

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Investigation on Influence of Instrumentation and Set Up‘s

1. Introduction

Measurements of gaseous and particulate emissions of diesel engine driven vehicles are mainly done using constant volume samplers (CVS) or partial flow dilution tunnels. The aim of such measurements is to quantify the contribution of pollutants to ambient air at the tail pipe. Whereas gaseous measurements enable the accurate evaluation of such contributions this is not the case for particulate measurements. Characteristics of particles such as size, number, chemical properties and mass are sensitively depending on the sampling process. It will be shown, how sampling parameters such as dilution ratio, material and heating temperatures of gas conducting tubes influence the measured quantities. In the case of nanoparticle measurement they additionally give rise to artefacts. As a consequence such measurements are in many cases not representing the real contribution of particulate pollutants to ambient air from the tail pipe.

Main objective of the measuring program was to compare in a first step nanoparticle measurement and filter mass analysis of a modern diesel passenger car on a roller dynamometer with CVS with those of an identical diesel engine on a test bench with partial flow dilution tunnel.

The variation of sampling parameters on the vehicle test setup is limited within a standardized range. The engine test setup was therefore built up to vary several of the sampling parameters to evaluate in a second step their influences on the measured quantities.

The measurements and tests have been carried out in collaboration with Volkswagen Wolfsburg. The present proceedings as a first part are focussed on the description of the experimental setup, measuring methods and on some influences of the setup. In the second part of S. Carli, Volkswagen a number of nanoparticle measurement and filter analysis results for varied measuring conditions will be presented.

2. Measuring program

The following measuring and analyzing methods have been applied to characterize the particulate emissions of the diesel engine and passenger car.

<u>Nanoparticle measurement</u>

- Scanning mobility Particle Sizer (SMPS) for particle size distributions related to mobility diameter [Wang et al, 1990]
- Electrical Low Pressure Impactor (ELPI) for real time particle size distribution related to aerodynamic diameter
- Real time Diffusion Charging (DC) sensor for active surface [Keller et al. 2001] and Photoelectrical Aerosol Sensor (PAS) for soot service [Burtscher et al. 1994)

Filter analysis

- Gravimetric Particulate Mass (PM) according to the standardized procedure for diesel engines [EURO]]
- Further analysis of the gravimetric PM filters on the SOluble Fraction (SOF), INSOluble Fraction (INSOF) and sulfates using X-Ray Diffraction (XRD)
- Elemental Carbon (EC) and Organic Carbon (OC) using the coulometric reference method for occupational exposures on working places [BGI]

The tests on the diesel engine were done on constant load operating conditions. The passenger car was additionally tested in transient NEDC cycles.

Both engines where tested with standard fuel EN 590 (300 ppm S) and low sulfur fuel (25 ppm S).

Additional tests have been carried out on a laboratory setup with test aerosol generators to evaluate the influence of different tube materials on the loss of nanoparticles.

3. Motivation

Inconsistent results in particulate measurements with varied sampling conditions where motivation for a deeper understanding of the influences from the sampling parameters as well as the fuel properties and exhaust afterteatment devices.

Fig. 1 shows an example of such inconsistency

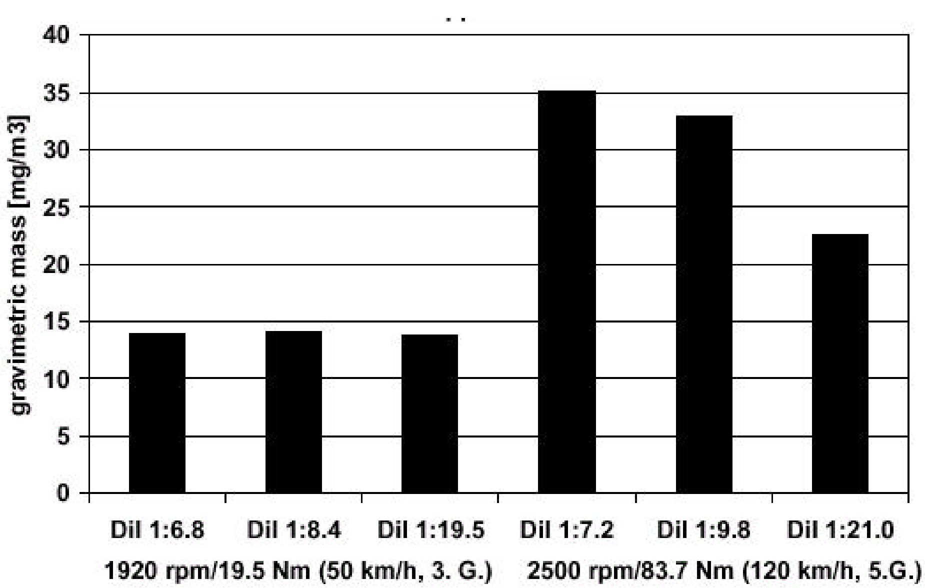

Fig. 1 PM analysis on pasenger car diesel engine with 300 ppm S fuel on test bench with partial flow dilution tunnel

Gravimetric PM of a diesel engine with oxidation catalyst (oxikat) is evaluated for low load (corresponding to 50 km/h, 3rd gear) and high load (corresponding to 120 km/h, 5th gear) operating conditions. The PM is analyzed at 3 different dilution ratios in the dilution tunnel.

Whereas no influence of the dilution ratio is observed at low load condition a clear and reproducible effect is observed at high load condition where significally more mass is collected on the PM filter at lower dilution.

In Fig. 2 size contributions are compared which have been simultanuously measured for low and high load using to 2 different diluting methods.

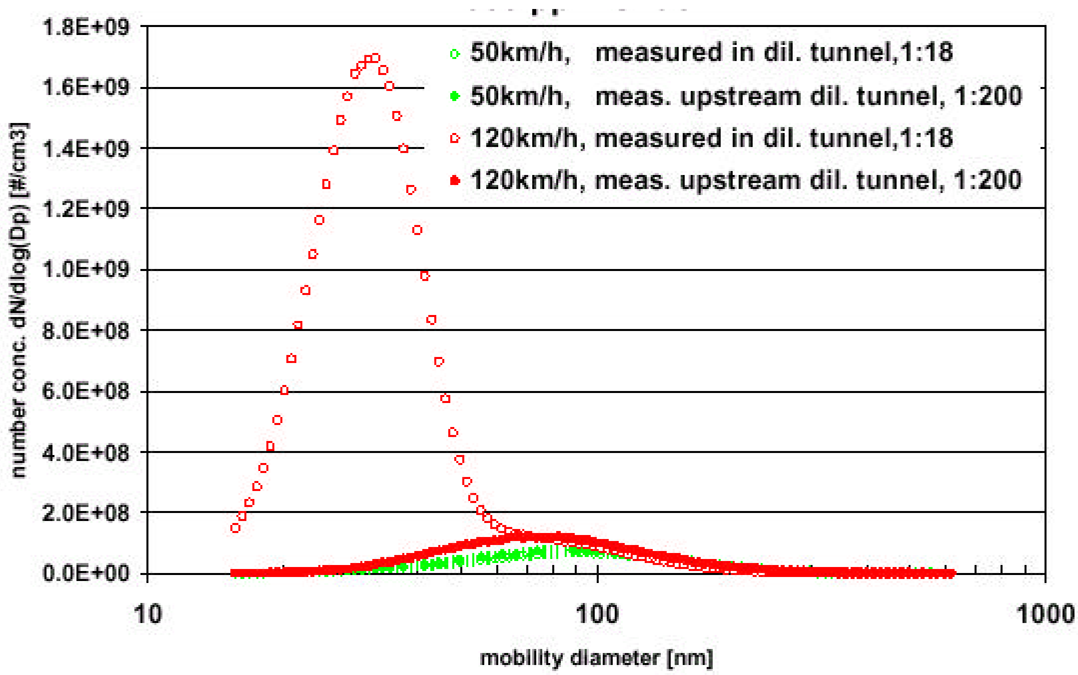

Fig. 2 Size distributions measured on a passenger car diesel engine with 300 ppm S fuel and with 2 different diluting methods

The nanoparticles are sampled at the tail pipe with a partial flow dilution tunnel and a rotating disk diluter. The differences are the much higher dilution factor and the heated dilution air of the rotating disk diluter.

There is a good agreement at low load after the 2 diluting processes both showing the typical accumulation mode of soot particles in the 80 - 100 nm mode diameter range.

A completely different view is given for high load. High dilution with heated dilution air shows a similar accumulation mode where as the size distribution after lower dilution in the tunnel is dominated by one order of magnitude more particles in the nucleation mode range below 50 nm.

It is obvious that these nanoparticles stem from the sampling and dilution process. Their contribution to gravimetric PM-measurement in standard dilution tunnels can explain the inconsistency shown in Fig. 1.

4. Measuring Setups, Tests

4.1 Passenger Car on Roller Dynamometer with CVS

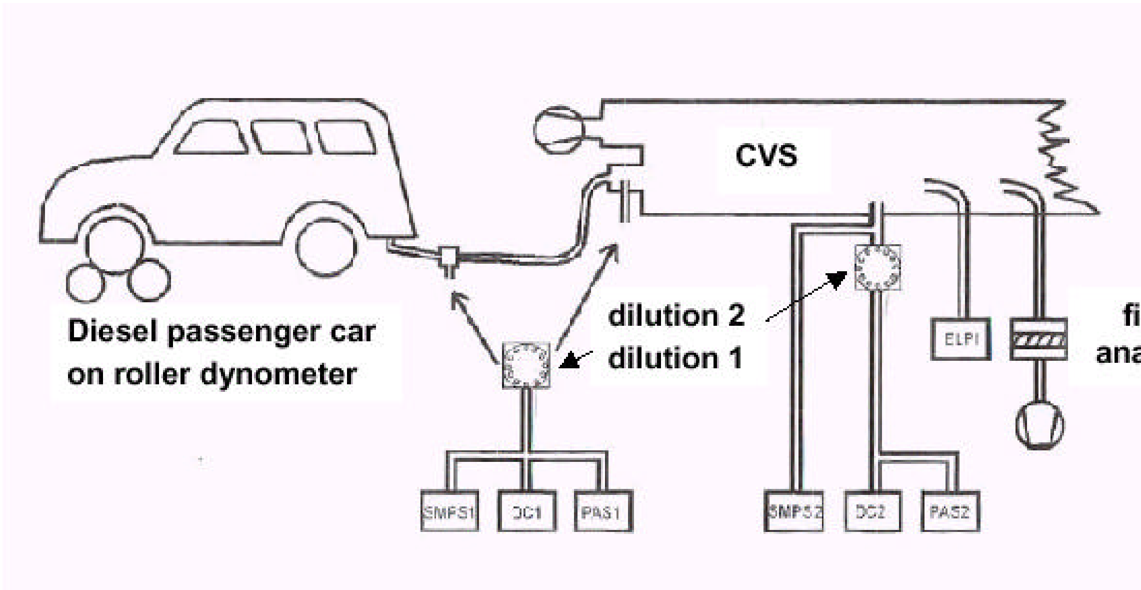

Fig. 3 Measuring setup for passenger car

A VW Passat passenger car with 1.9l/85 kW unit injector diesel engine and an oxikat is driven on a standard roller dynamometer with CVS dilution tunnel which is connected via 5 m thermically insulated transfer line to the tail pipe.

Nanoparticle characteristics are measured with SMPS, PAS and DC simultaneously after 2 different dilution processes. In the CVS the dilution factors are below 20 while a rotating disk dilutor with heated dilution air (80 °C or 120 °C) dilutes the exhaust by factors of a few hundred. The exhaust to the rotating disk diluter is alternatively sampled at the tail pipe or at the input to the CVS.

For some of the tests the partial flow dilution tunnel (see chapt. 4.2) used on the engine test bench was connected to the tail pipe or at the input to the CVS.

The diluted aerosol in the CVS was additionally analyzed in an ELPI and by loading filters for gravimetric PM, coulometric carbon, SOF/INSOF and sulfate analysis.

Fig. 4 VW Passat Variant with diesel engine on roller dynamometer with CVS and nanoparticle measuring systems

The passenger car was tested in the

- 4 continuous loads 50 km/h, 3rd gear, 50 km/h, 4th gear, 100 km/h, 5th gear, 120 km/h, 5th gear
- NEDC transient cycles with cold and warm start
- with 300 ppm S (EN590) and 25 ppm S fuel

The following tests have been carried out

- Comparison of mobility with aerodynamic size classification
- Simultaneous measurement with different diluting systems
- Influence of transfer line from tail pipe to CVS
- Influence of SMPS configuration

Fig. 5 Exhaust probe of rotating disk diluter to tail pipe of passenger car

The rotating disk diluter MD19-2E shown in Fig. 5 and 6 has been proven as a valuable useful tool for nanoparticle online measurements on tail pipe systems.

- High dilution factors and heated dilution air prevents the formation of volatile nanoparticles by spontaneous nucleation of gaseous compounds in the exhaust.
- It is connected from one to the next sampling point within a few minutes which is very useful when the exhaust is measured at different spots of tail pipe system.

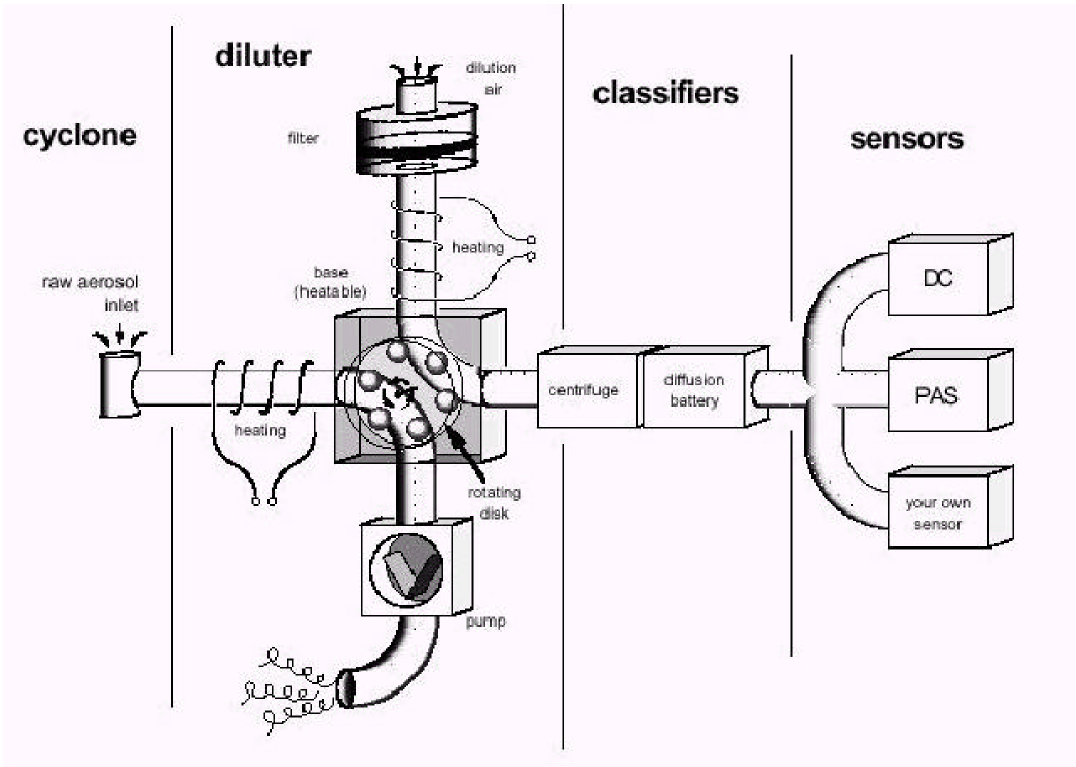

Fig. 6 Principle operation diagram of rotating disk diluter

4.2 Diesel Engine on Test Bench with Partial Flow Dilution Tunnel

A VW Passat unit injecttor diesel engine was tested on the test bench shown in Fig. 7.

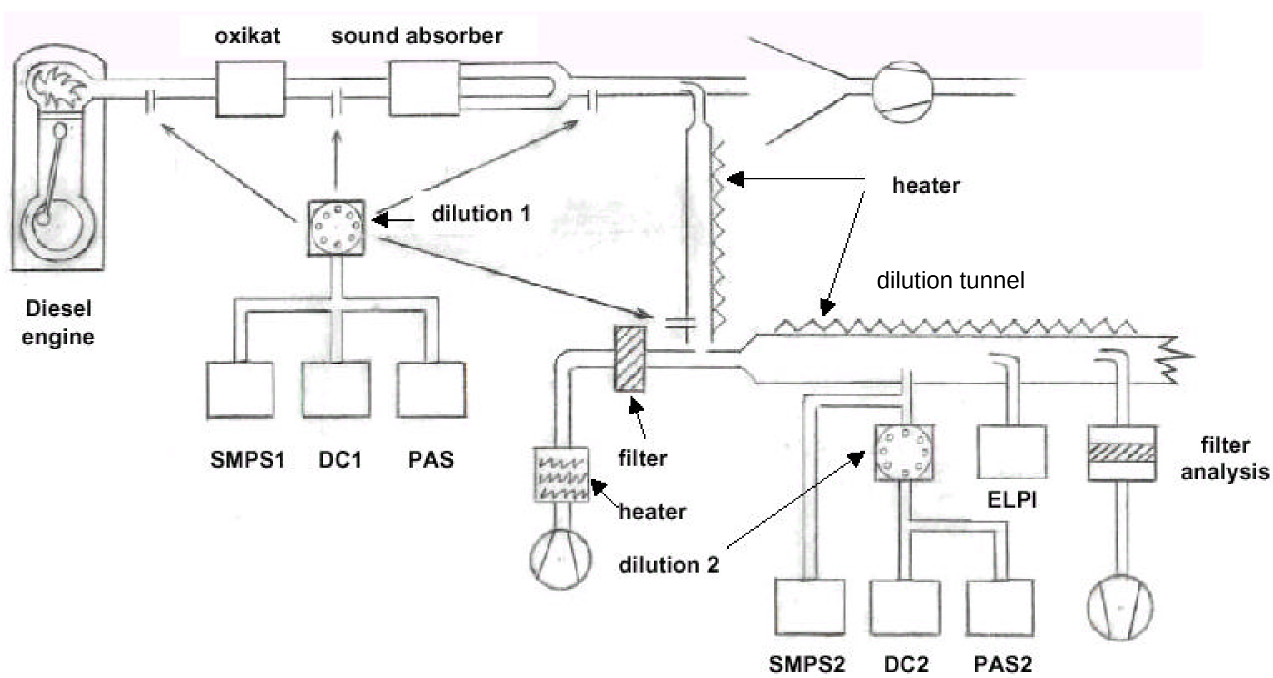

Fig. 7 Unit injection diesel engine on test bench with partial flow dilution tunnel

Diesel engine and exhaust system to tail pipe are identical to that of the tested passenger car. A partial flow is guided through a heated transfer line to a partial flow dilution tunnel. This tunnel is equipped with a heater to achieve regulated dilution air temperatures up to 150 °C. An additional heater keeps the temperature of the measuring gas from the partial flow inlet over the tunnel length to the sampling probes.

Nanoparticle measurements in the dilution tunnel were compared with simultaneous measurements in the raw gas; after the engine, after the oxikat, at the tail pipe and at the inlet to the dilution tunnel.

The operating conditions for the engine were

- 4 continuous loads corresponding to the speeds of the passenger car on roller dynamometer
- 300 ppm S (EN590) and 25 ppm S fuel

The measuring setup was designed to carry out the following additional tests:

- Influence parameters on spontaneous nucleation to volatile nanoparticles in the sampling process
- Influence of dilution ratio to gravimetric mass measurement
- Influence of sampling probe construction on nanoparticle measurement and gravimetric filter analysis in the dilution tunnel
- Emission of nanoparticles in the range of 3 – 6 nm from the engine

4.3 Loss of Nanoparticle in Tube Materials

Nanoparticles get lost in gas tubes by diffusion, coagulation, electrostatic effects and thermophoresis. This first 2 effects are independing from the properties of tube material and can be estimated. Losses by electrostatic effects depend mainly from the electrical conductivity. Metallic tube of stainless steel and copper are therefore preferred tube-materials in nanoparticle measuring setups.

Flexible gas tubes which are easier to maintain have been tested in the measuring setups shown in Fig. 8 and compared with the characteristics of metallic tubes.

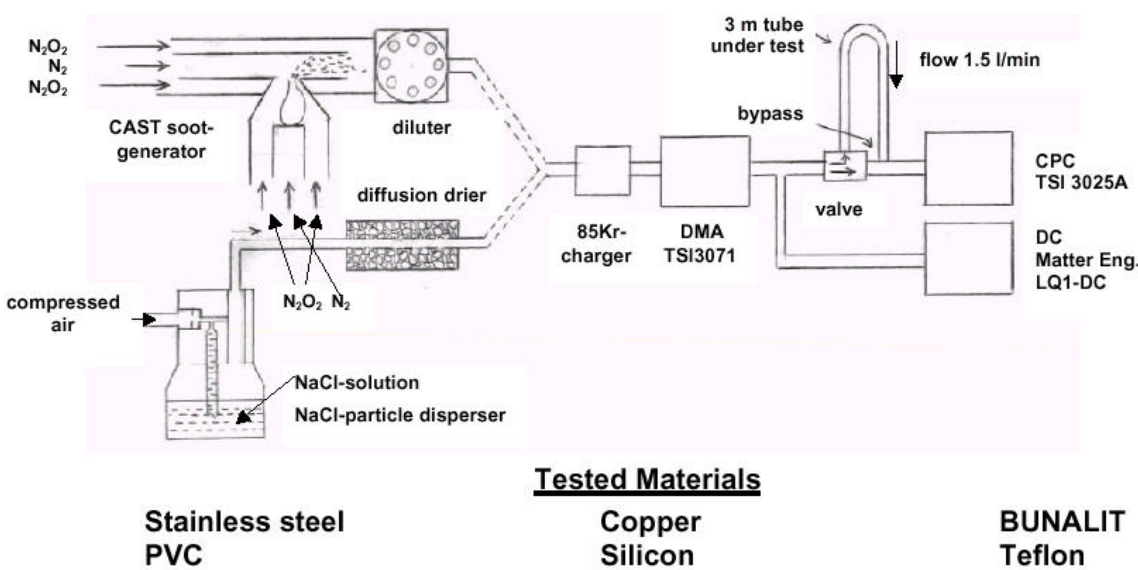

Fig. 8 Measuring setup to test nanoparticle losses depending on gas tube material

The tests have been carried out using 2 different types of single charged 30, 100 or 200 nm particles. Combustion particles have been generated in a CAST (**C**ombustion **A**erosol **ST**andard) soot generator, producing diesel like nanoparticles reproducibly tunable in size and concentrations. Identical tests were done with NaCl-particles from a disperser filled with NaCl solution of 50 ng NaCl/100 ml/$H_2$0. The number concentration behind 3 m of tested tube was compared to that behind a short bypass. With number concentrations in the range of a few 10^4 part./cm^3 no coagulation but only diffusion losses of a few % have to be taken into account as losses independent of the tube material.

5. Influences of Measuring Conditions

5.1 Comparison of Dilution and Influence of DMA Gas Flows

In most of the tests on the 2 test benches simultaneous nanoparticle measurements have been carried out using 2 different sampling and diluting procedures. Direct SMPS-measurement in the dilution tunnels is compared to SMPS-measurement in the raw gas, sampled and diluted with a MD19-2E rotating disk diluter.

The influence of the diluter as well as the gas flows in the DMA (high/low flow) have been evaluated connecting one SMPS-directly and the other system via the MD19-2E to the test aerosol.

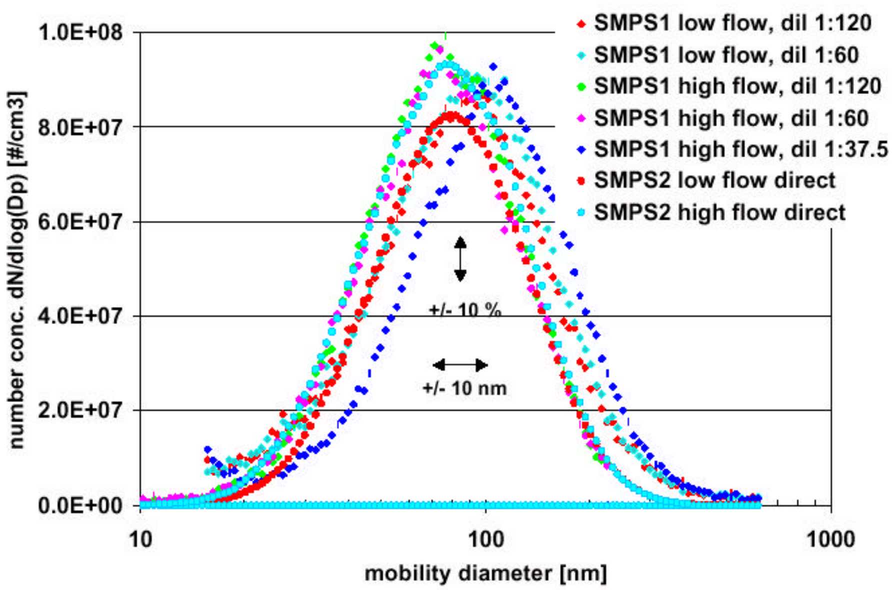

Fig. 9 Comparison of SMPS-measurement for different DMA-gas flows and with additional dilution

As shown in Fig. 9 the influence of dilution and DMA gas flows are within a standard deviation of 10 % for the number concentration and 10 nm for the size.

5.2 Influence of Sampling Probe to Partial Flow Dilution Tunnel

5 different types of sampling probes as shown in Fig. 10, collecting the exhaust at the tail pipe into the transfer line to the dilution have been tested on their influence on nanoparticle measurement and gravimetric PM analysis.

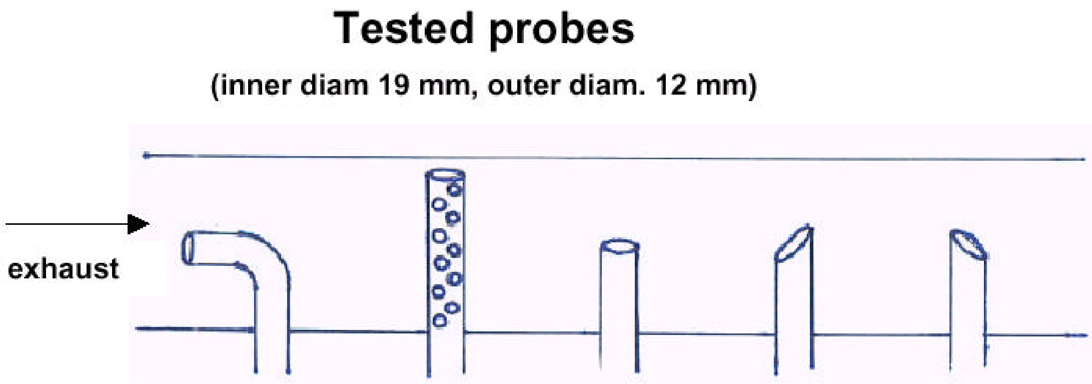

Fig. 10 Sampling probes for exhaust from tail pipe to partial flow dilution tunnel

No influence within a standard deviation of 5 % has been observed. Since the majority of PM stems from particles in the submicron size range non isokinetic influences in the sampling can be neglected.

5.3 Loss of Nanoparticles depending on Tube Materials

- No additional losses to diffusion losses have been observed for stainless steel, copper and the cheep flexible BUNALIT tube (BUNALIT Perbunan E 65, Angst + Pfister, www.angst-pfister.com).
- PVC-tubes provide similar characteristics except for 30 nm particles in new tubes where additional losses are observed.
- Due to electrostatic effects the losses in teflon- and silicon tubes are 1 order of magnitude larger than the diffusion losses. The losses decrease when the tubes are polluted by particles after use.

Generally tubes of highly insulating material should not be used for nanoparticle measurement. Nevertheless non electrically conducting flexible material of lower insulation exists as an alternative to metal tubes.

6. References

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