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Diesel smoke measurements – optical methods vs. particle counting

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Motivation and objectives

The exhaust from diesel engines in vehicles and construction machinery must be checked periodically and on site. For this inspection a short procedure without a test bench is required. Since many years the smoke is measured with a free acceleration test using opacimetry.

Engines of a new generation and those equipped with particle filters emit very little smoke and opacimeters operate at their limits of detection . More sensitive measuring methods have to be investigated and defined in future regulations (Schlatter and D'Urbano).

This work compares the most sensitive measuring method – the particle number concentration measurement – with opacimetry and scattering light method. Their limitations in sensitivity and open questions concerning calibration and comparability are discussed. For new regulations consensus on these questions has to be established first.

Particle measurements with scattered light

The experimental work was done with the instrument MPM 4 (from MAHA). This instrument was specially designed for the purpose of testing engines equipped with particle filters.

The „scattering light instrument" (SCA) measures particles by detecting the intensity of scattered red light at an angle of 90° by particles. The light intensity is a measure of the particle mass concentration in the aerosol (unit: mg/m^3). As the interaction between light and particle is probed the optical properties (depending on the size and the chemical composition of the particle) strongly influence the measuring signal. The calibration of the light intensity my means of a known particle mass concentration was done in the laboratory of the instrument manufacturer.

The particle size influences both the calibration curve and the uncertainty of the result. A good assumption is that the scattered light intensity is proportional to the particle mass concentration. Yet, it is known that the light intensity decreases with smaller particles (Faxvog and Roessler, 1978). This is found experimentally from the comparison of calculated particle mass concentration from the particle number measurement with the values from the SCA (Figure 1). In order to define a particle size detection limit for SCA following model is applied. From the size distribution the mass concentration is calculated for particles above a a size limit. The best curve fit (Figure 2) was found with a size limit at d = 170 nm and this is defined as the detection limit.

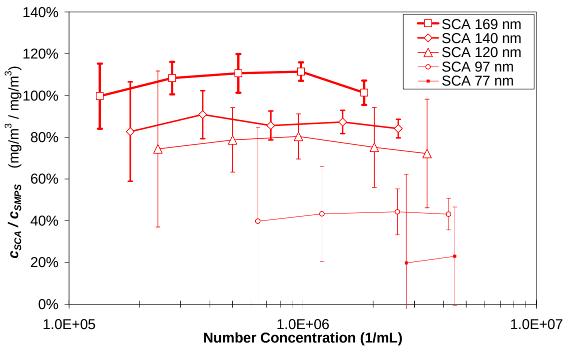

Figure 1: Fraction of combustion particle mass concentration measured with SCA and calculated from SMPS for various particle diameters (d_g and GSD 1.6). The bars indicate standard deviations from the measurements.

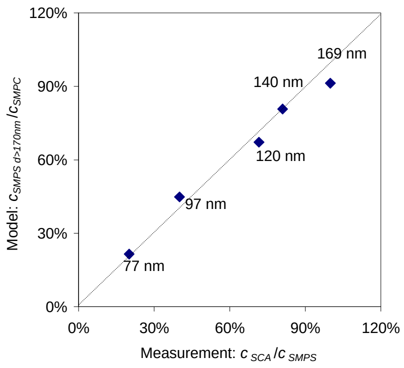

Figure 2: Comparison of mass concentrations measured with SCA and calculated with model using SMPS measurements and a cut-off diameter at d = 170 nm.

Light extinction measurement – opacimeter

A light extinction instrument (EXT) measures the reduction of a light beam by particles in the aerosol. This is the legally demanded method for the periodic smoke test of road vehicles. This measuring method was developed for diesel engines without particle filters.

The instrument used for the smoke measurements (DOT from Sensors Inc.) indicates the light extinction with a resolution of 0.01 m^{-1}. An uncertainty of 0.15 m^{-1} was sufficient for vehicles at that time. But nowadays the measured signal to noise and drift ratio is not sufficient any more (Figure 3). Therefore no measurement at lower concentration was possible with the available instrument type.

Comparison of instruments

A good parameter to evaluate the limits of a particle measuring instrument is the ratio of the signal divided by sum of noise and drift. In the present study the instrument SCA turned out to be almost and EXT absolutely not satisfactory (Figure 3).

The signal noise is calculated as standard deviation of the signal and shows little change with the particle concentration, but increases with decreasing particles sizes. The signal drift becomes important at small particle concentrations. Both instruments suffer from a drift of zero signal, that could be a thermal problem of the detector, soiling of the optics or just a mechanical adjustment problem.

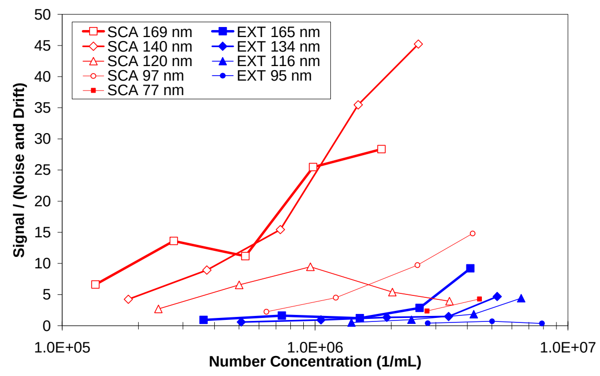

Figure 3: Signal to noise and drift ratio for particle measurements with SCA and EXT for particle diameters between 95 nm and 169 nm.

Requirements of future instruments

Instruments for the periodic measurement of particle emissions from new diesel engines and those equipped with particle filters must be robust and more sensitive than today's instruments. Additionally they must be applicable with a simple measurement procedure (as e.g. the free acceleration test).

In the further development of particle measuring instruments four key issues have to be take into account:

1. The calibration of the instrument must be valid for various particle size distributions.
2. The measurement procedure shall be fast, easy to handle and reproducible.
3. The limit of detection for the particle size must be lowered e.g. particle size < 100 nm.
4. The limit of detection for the particle concentration must be lowered below a number concentration of 10^4 mL^{-1} or a mass concentration 10^{-2} mg/m^3 or an extinction coefficient of 10^{-4} m^{-1}.

Recent improvements for more sensitive smoke meters with various measuring principles show feasibility and development should be continued.

References

Faxvog, Fred R., and Roessler, David M. (1978) Carbon aerosol visibility vs particle size distribution, Applied Optics, Vol 17-16, p 2612 – 2616
Schlatter, J., D'Urbano, G., (2007) Portable Particle Counter for Engines with Diesel Particle Filters, 11th ETH-Conference on Combustion Generated Nanoparticles, August 13th to 15th 2007

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