Extended Summary to the Poster

Investigations of Particles Emitted by a DI Gasoline Engine under Stationary and Transient Conditions

Wolfgang Mühlbauer, Ulrich Leidenberger, Sebastian Lorenz, Sebastian Lehmann and Dieter Brüggemann

Department of Engineering Thermodynamics and Transport Processes,
Bayreuth Engine Research Center (BERC), Universität Bayreuth, Germany

Recent studies reveal that there is a strong relationship between atmospheric particulate matter (PM) and adverse human health impacts associated with mortality and morbidity [1–3]. It is well known that internal combustion engines contribute to a significant fraction of the total particulate matter [4]. To reduce these emissions in Europe, legislations were established which currently regulate particulate mass and will also limit particulate number for diesel engines as from 2012 (Euro 5b). For gasoline engines a particulate number limit will be introduced in 2014 (Euro 6) as well [5,6]. As a consequence, particulate filters may become necessary for particulate emission control of gasoline engines. As one knows from diesel particulate filters, the knowledge of the physicochemical properties of the emitted particles is essential for efficient regeneration procedures [7,8].

Parameter Study at an Engine Test Bench (Audi 3,2L V6 FSI Engine)

A parameter study is carried out with a modern Audi direct injection gasoline engine (Table 1) by the Department of Engineering Thermodynamics and Transport Processes of the University of Bayreuth. The operating points were precisely analyzed by SMPS measurements, High-Resolution Transmission Electron Microscopy (HRTEM) and thermogravimetry. For the SMPS measurements a rotating disc diluter and a thermodenuder are used to condition the sample flow prior to the measurements. HRTEM samples (copper grids, lacey carbon film coated) are taken directly out of the tailpipe.

Table 1: Technical data of the Direct Injection Gasoline Engine

Cylinders	6
Displacement	3123 cm^3
Power	188 kW at 6500 rpm
Torque	330 Nm at 3250 rpm
Injection System	3 – 10MPa injection pressure
Fuel	Gasoline with up to 5 % ethanol
Cooling System	Water, 20 – 100 ℃

First of all, measurements with a Scanning Mobility Particle Sizer (SMPS) were conducted at different positions of the engine exhaust aftertreatment system (before “three way” catalytic converter, after catalytic converter and after NOx storage catalytic converter), under different engine load conditions at constant engine speed and under transient engine operating conditions. SMPS analysis at 2000 rpm and 20% engine load shows clearly higher particulate emissions before the “three way” catalytic converter than after. Concentrations before and after the NOx storage catalytic converter are almost the same. Further measurements illustrate that with increasing engine load the particulate emission concentration increases and furthermore the particle mobility diameter increases with increasing engine load. Moreover, particle emission measurements were carried out under transient operating conditions. Analysis during the cold start period at 1000 rpm and 20 % load exemplify a high influence of the engine temperature on the concentrations of emitted particles after the three way catalytic converter. The mean mobility diameter decreases with increasing engine temperature. Also SMPS measurements in the European Driving Cycle (NEFC) were carried out to study the influence of acceleration and deceleration procedures at two particle mobility diameters (35 nm and 70 nm). The measurements show that the particle concentration (70 nm) decrease with consecutive testing period during the urban driving cycle while the particle concentration with mobility diameter 35 nm remain almost constant. In the extra-urban driving cycle the particle concentration for particles with 70 nm as well as for 35 nm diameter are clearly lower than in the urban cycles.

In addition, particles emitted by the gasoline engine were sampled on TEM grids at 2000 rpm and 100 % engine load after three way catalytic converter. The HR-TEM images with a Zeiss Libra 200FE show a high variance in primary particulate diameter. Another parameter study at our institute with a modern Audi direct injection diesel engine demonstrates that with increasing injection pressure the primary particulate diameter and its variance decrease. This indicates a high influence of the injection pressure on the variance of the primary particulate diameter (gasoline engine: 3 – 10 MPa injection pressure, diesel engine: 50 – 160 MPa injection pressure).

Conclusion and Future Work

First results of the study show:

- Lower particle concentration after three way catalytic converter than before; concentrations before and after NOx storage catalytic converter almost the same.
- Decreasing peak particle diameter and concentration with decreasing engine load.
- Decreasing particle concentration and diameters during the cold start period
- Clearly lower particle concentration in the extra-urban than in the urban driving cycle (NEFC).
- High variance of primary particles emitted by a direct injection gasoline engine (influence of injection pressure).

To prove the assumption that with higher injection pressures the variance of the primary particle diameter decreases, further TEM samples of particles emitted by a direct injection gasoline engine have to be taken at different engine operating conditions. For determining differences in the oxidation behaviour of the samples, thermogravimetric analysis will be conducted for stationary as well as for transient operating conditions. Moreover, the influence of gasoline engine parameters (boost and injection pressure, ignition timing) on the physicochemical properties has to be studied in the future.

References

[1] Oberdörster G.: *Pulmonary effects of inhaled ultrafine particles*, International Archives of Occupational and Environmental Health, 2000, **74**(1), S. 1–8.

[2] Lanki T. et al.: *Can We Identify Sources of Fine Particles Responsible for Exercise-Induced Ischemia on Days with Elevated Air Pollution? The ULTRA Study*, Environmental Health Perspectives, 2006, **114**(5), S. 655–660.

[3] Anenberg S. C. et al.: *An Estimate of the Global Burden of Anthropogenic Ozone and Fine Particulate Matter on Premature Human Mortality Using Atmospheric Modeling*, Environmental Health Perspectives, 2010, **118**(9), S. 1189–1195.

[4] Collings N., und Graskow B. R.: *Particles from internal combustion engines - what we need to know*, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 2000, **358**(1775), S. 2611–2623.

[5] Europäisches Parlament: *Verordnung (EG) Nr. 715/2007 des Europäischen Parlaments und des Rates vom 20. Juni 2007 über die Typgenehmigung von Kraftfahrzeugen hinsichtlich der Emissionen von leichten Personenkraftwagen und Nutzfahrzeugen (Euro 5 und Euro 6) und über den Zugang zur Reparatur- und Wartungsinformationen für Kraftfahrzeuge*, 2007, S. 1–16.

[6] Europäische Kommission: *Verordnung (EG) Nr. 692/2008 der Kommission vom 18. Juli 2008 zur Durchführung und Änderung der Verordnung (EG) Nr. 715/2007 des Europäischen Parlaments und des Rates über die Typgenehmigung von Kraftfahrzeugen hinsichtlich der Emissionen von leichten Personenkraftwagen und Nutzfahrzeugen (Euro 5 und Euro 6) und über den Zugang zu Reparatur- und Wartungsinformationen für Fahrzeuge*, 2008, S. 1–136.

[7] Müller J.-O. et al.: *Diesel engine exhaust emission: oxidative behavior and microstructure of black smoke soot particulate*, Environmental Science & Technology, 2006.

[8] Leidenberger U. et al.: *Experimental Studies on the Influence of Diesel Engine Operating Parameters on Properties of Emitted Soot Particles*, Combustion Science and Technology, 2012, **184**(1), S. 1–15.

W. Mühlbauer, U. Leidenberger, S. Lorenz,
S. Lehmann and D. Brüggemann

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LEHRSTUHL FÜR TECHNISCHE THERMODYNAMIK UND TRANSPORTPROZESSE
PROF. DR.-ING. D. BRÜGGEMANN

www.lttt.uni-bayreuth.de

MOTIVATION

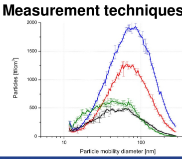
- Strong relationship between atmospheric particulate matter (PM) and adverse human health impacts associated with mortality and morbidity
- Significant fraction of the total particulate matter from internal combustion engines
- For diesel engines: Limitation of particulate mass as well as particulate number as from 2012
- For direct injection gasoline engines: Limitation of particulate mass and of particulate number as from 2014 (limit will be fixed)
- Particulate filters as an efficient method for particulate emission control in gasoline engines
- Knowledge of physicochemical properties of the emitted particles essential for efficient regeneration procedures of particulate filter systems

TEST BENCH / MEASUREMENT TECHNIQUES

Technical data of the Direct Injection Gasoline Engine at an engine test bench

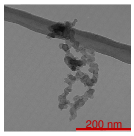
Audi Euro 4 FSI V6 engine	
Cylinders	6
Displacement	3123 cm^3
Power	188 kW at 6500 rpm
Torque	330 Nm at 3250 rpm
Injection system	3 – 10 MPa injection pressure
Fuel	Gasoline with up to 5 % ethanol
Cooling system	Water, 20 – 100 °C

Measurement techniques



Scanning Mobility Particle Sizer (SMPS):

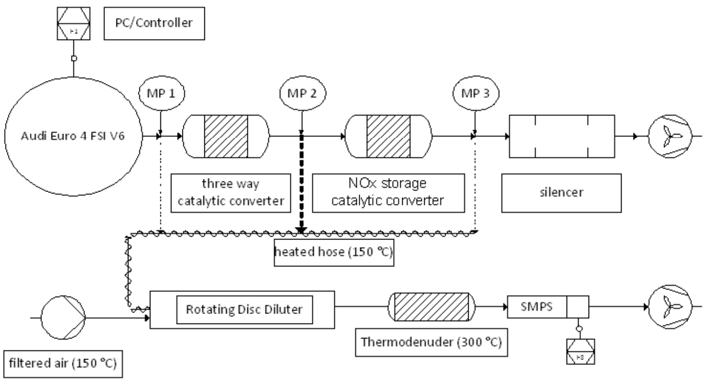
particle size distribution



Microscopy:

Agglomerate / primary particle size, morphology

MEASUREMENT SETUP



OPERATING CONDITIONS

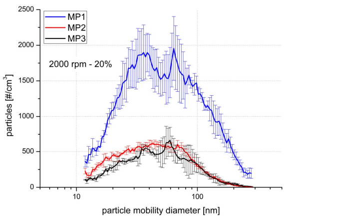
- **Stationary operation**: load variation at 1000 rpm, 2000 rpm and 3000rpm

Engine Speed [rpm]	Posicon [%]	Torque [Nm]	Lambda [-]	Injection Pressure [MPa]
1000	20	95	1	3.6
1000	50	223	1	4.2
1000	100	230	0.92	4.2
2000	20	22	1	3.0
2000	50	272	1	6.4
2000	100	280	0.92	6.5
3000	20	5	1	2.8
3000	50	268	1	8.0
3000	100	281	0.90	8.0

- **Transient operation**: New European Driving Cycle (NEDC), cold start conditions
- **Variation of the measurement position**: before "three way" catalytic converter (MP1) , after three way catalytic converter (MP2), after NOx storage catalytic converter (MP3)

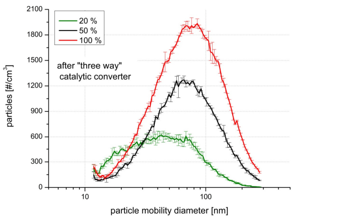
RESULTS

Influence of the measurement position



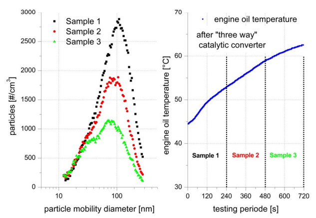
- High reduction of particle concentration after three way catalytic converter
- Particle concentration after catalytic converter and after NOx storage catalytic converter almost the same

Influence of different load points at 2000 rpm



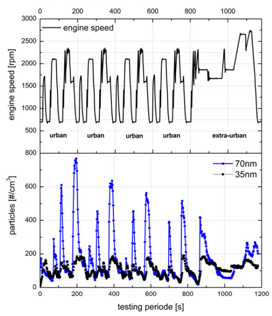
- Decreasing particle concentration and smaller mean particulate diameters with decreasing engine load

Influence of the operating temperature (cold start conditions, 1000 rpm-20%)



- High influence of the engine temperature on the emitted particulate emissions
- Mean particle diameter decreases in the warm-up period

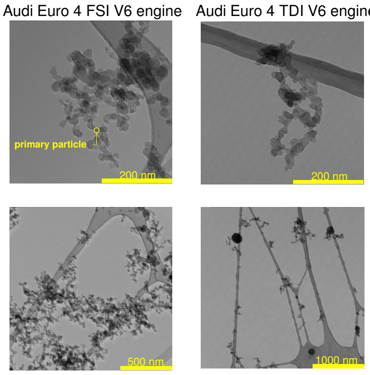
Particle concentration under transient conditions (NEFC)



- Decreasing particle concentration (35 and 70 nm diameter) with consecutive testing period
- Clearly lower particle concentration in the extra-urban than in the urban driving cycle

High-Resolution Transmission Electron Microscopy (HRTEM) to determine the primary particle size

Audi Euro 4 FSI V6 engine Audi Euro 4 TDI V6 engine



Comparison of primary particle size for a DI gasoline and diesel engine by HRTEM images (about 300 primary particles):

Operating Point	Variance in size	Standard deviation in size	median primary particle size
TDI-60MPa	73	8.5	22.9 nm
TDI-75MPa	64	8.0	21.5 nm
FSI-6,5 MPa	154	12.4	22.5 nm

- Primary particles emitted by the gasoline engine have a higher variance than those emitted by the diesel engine (primary particles with a high number of different diameters emitted by the gasoline engine)
- Indicates an influence of the injection pressure (FSI: 3 – 10 MPa, TDI: 50 – 160 MPa) on the variance of primary particle diameters

Conclusion

- Lower particle concentration after three way catalytic converter than before; almost the same concentration before and after NOx storage catalytic converter
- Decreasing peak particle diameters and particle concentration with decreasing engine load
- Decreasing particle concentration and diameters during the cold start period
- Clearly lower particle concentration in the extra-urban than in the urban driving cycle (NEFC)
- High variance of primary particles emitted by a direct injection gasoline engine (influence of injection pressure)

Future Work

- Further HRTEM samples to prove the assumption that the variance decreases with higher injection pressure
- HRTEM images and EELS measurements for particle morphology and carbon bounding structure as well as thermogravimetry for oxidation behavior of the soot samples
- Influence of engine parameters on physicochemical properties of the emitted particles