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INFLUENCING (NANO)PARTICLE EMISSIONS OF 2-STROKE SCOOTERS

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ABSTRACT−Limited and nonlimited emissions of scooters were analysed during several annual research programs of the Swiss Agency of Environment Forests and Landscape (SAEFL, BUWAL). Small scooters, which are very much used in the congested centers of several cities are a remarkable source of air pollution. Therefore every effort to reduce the emissions is an important contribution to improve the air quality in urban centers. In the present work detailed investigations of particle emissions of different 2-stroke scooters with direct injection and with carburetor were performed. The nanoparticulate emissions with different lube oils and fuels were measured by means of SMPS, (CPC) and NanoMet. Also the particle mass emission (PM) was measured with the same method as for Diesel engines. It can be stated, that the oil and fuel quality have a considerable influence on the particle emissions, which are mainly oil condensates. The engine technology influences the (nano)particle emissions by: mixture preparation, mixture tuning, oil consumption, postoxidation, quality, condition and temperature of the catalyst. Since the particulate emission of the 2-S consists mainly of lube oil condensates the minimization of oil consumption stays always an important goal.

KEY WORDS : 2-S emissions, (Nano)particles, Sampling, Oil quality 2-S, Fuel quality 2-S

NOMENCLATURE

AFHB : Abgasprüfstelle der Fachhochschule, Biel CH (Lab. For Exhaust Gas Control, Univ. of Appl. Sciences, Biel-Bienne, Switzerland)
AMF : Implementing Agreement on Advanced Motor Fuels
ARAI : Automotive Research Association of India
BUWAL: Bundesamt für Umwelt, Wald und Landschaft (Swiss EPA, SAEFL)
Carb. (C) : Carburetor
CPC : condensation particle counter
CVS : constant volume sampling
Cx : measuring serie "X" with Carburetor
DC : diffusion charging sensor
DMA : differential mobility analyzer
EMPA : Swiss Federal Laboratories for Materials Testing and Research
EPA : Environmental Protection Agency
ETHZ : Eidgenössische Technische Hochschule Zürich
EV : Erdöl-Vereinigung, Swiss Association of Oil Manufacturers
IEA : International Energy Agency
JRC : Joint Research Center, EU Laboratories, Ispra, Italy
MD : minidiluter
ME : Matter Engineering AG, CH NanoMet minidiluter + PAS + DC (+ThC), (+TD)
NP : nanoparticulates
PAS : photoelectric aerosol sensor
PM : particulate matter, particulate mass
PSD : particles size distribution
SAEFL: Swiss Agency for Environment, Forests and Landscape (Swiss EPA, BUWAL)
SAS : secondary air system
SMPS : scanning mobility particles sizer
SOF : soluble organic fractions
SUVA : Schweizerische Unfallversicherungsanstalt
TD : thermodesorber
ThC (TC) : thermoconditioner
TSDI (T) : Two Stroke Direct Injection
Tx : measuring serie "x" with TSDI
TTM : Technik Thermische Maschinen, CH
VOC : volatile organic compounds
VTT : Transport Research Center, Finland

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1. INTRODUCTION AND OBJECTIVES

In the annual investigation programs of AFHB mandated by the Swiss EPA (BUWAL) (Czerwinski, *et al.*, 2002a; 2003; 2002b; Czerwinski and Comte, 2003) the problem of particle mass and particle counts emissions of 2-S engines was particularly addressed. The work about influences of different lubricating oils, different fuels and different conditions of oxidation catalyst (Czerwinski *et al.*, 2003), showed in reality considerable potentials, but also necessities of further more extended, interdisciplinary research.

This situation led to the need of participation of several analytical laboratories and industrial partners and due to general interest and support a project network was created. In this network the Swiss Research Partners: TTM, AFHB, EMPA, ME, SUVA collaborate with several industrial partners and foreign research institutes, like JRC Ispra, VTT Finland, Toxicity Network France and ARAI India. This network is open to the interested parties to join it and it exchanges informations about the 2-S 2-wheelers research with the Annex XXXIII of IEA Implementing Agreement AMF, IEA (2005).

This paper represents the supplementing investigations and validations of the results from (Czerwinski *et al.*, 2003), which showed the influences of lube oils and fuels on the (nano) particulates.

The specific questions where:
- reproducibility of the influences of oils with different S-content,
- influences of different oils with the Aspen fuel,
- influences of engine technology: TSDI-Carburetor,
- check of sampling point and sampling procedure for nanoparticles.

2. INVESTIGATED SCOOTERS

The investigated scooters were:
Peugeot Looxor TSDI and Peugeot Looxor Carburetor (see Table 1).

Figure 1. shows these scooters in the measuring laboratory.

The Peugeot TSDI-System uses crankshaft driven air compressor. Gasoline is injected in the pressurised air of the feed rail where the premixing of air and fuel takes place. The air injector controls the admission of the rich mixture in the combustion chamber. The lubrication oil is dosed in the intake air of the engine by means of the oil pump.

For the vehicles with carburetor simple, conventional

Table 1. Data of the scooter Peugeot Looxor TSDI and Carburetor T.

	Peugeot	Peugeot
Vehicle identification	Looxor TSDI	Looxor
Model year	2002	2004
Transmission no. of gears	variomat	variomat
km at beginning	1400	0
Engine: type displacement cm^3 Number of cylinders	2 stroke 49.1 1	2 stroke 49.1 1
Cooling	Air forced	Air forced
Rated power kW Rated speed rpm Idling speed rpm	3.6 7800 1700	3.72 8100 1800
max vehicle speed km/h	45	45
Weight empty kg	94	94
Mixture preparation	direct injection with automatic oil pump	carburetor with automatic oil pump
Catalyst	yes	yes + SAS (secondary air system)
Catalyst data	Pt/Rh 5/1 50 g/ft^3 200 cpsi metal support ∅ 60,5 / L 40	Pt/Pd/Rh 1/28/1 50 g/ft^3 100 cpsi metal support ∅ 60,5 / L 40

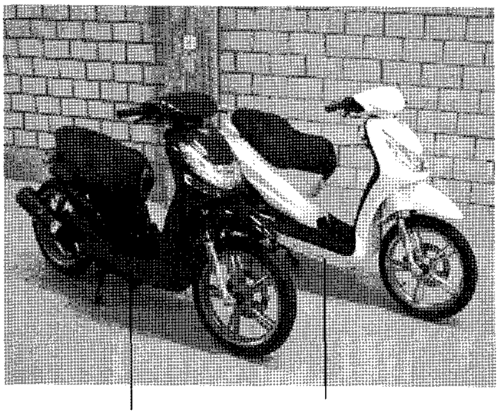


Figure 1. Investigated scooters: left TSDI, right Carburetor.

carburetors with a cable-controlled throttle body and needle are used. The lubrication oil is also dosed in the intake air of the engine.

3. PARTICLE SIZE ANALYSIS AND MEASURING SET-UP

In addition to the gravimetric measurement of particulate mass, the particle size and counts distributions were analysed with following apparatus:

- SMPS – Scanning Mobility Particle Sizer, TSI (DMA TSI 3071, CPC TSI 3025 A)
- NanoMet – System consisting of:
  - PAS – Photoelectric Aerosol Sensor (Eco Chem PAS 2000)
  - DC – Diffusion Charging Sensor (Matter Eng. LQ1-DC)
  - MD19 tunable minidiluter (Matter Eng. MD19-2E, see Figure 1).
  - Thermoconditioner (TC) (i.e. MD19 + postdilution sample heating until 300°C)
  - Thermodesorber (TD)

A detailed description of those systems can be found in the manufacturers informations. The sampling and measuring set-up during the tests shows Figure 2.

In the research of sampling for NP-analysis several variants of sampling were used, which are alternatively represented in Figure 2.

The nanoparticulates measurements were performed during cold acceleration to a constant speed and a following warm-up period with CPC and NanoMet and at the constant speed (warm) with SMPS and NanoMet.

4. MEASURING PROCEDURES AND OILS

The sampling for nanoparticle analysis took place at tailpipe through MD19, as in the previous work, (Czerwinski *et al.*, 2003; 2005). The gravimetric measurements of PM were performed at the CVS tunnel (with same method as for Diesel cars).

Also the measuring procedure was similar, as in (Czerwinski *et al.*, 2003) cold start (20–25°C) – acceleration to 40 km/h and v = const = 40 km/h. It was decided to increase the speed (previously 30 km/h) to guarantee the catalyst light off with all researched combinations "vehicle-fuel-oil".

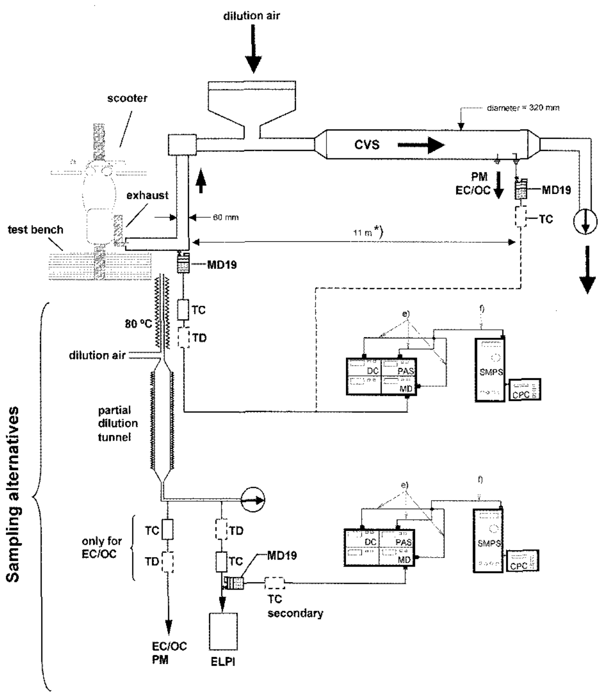
The temperature and CO after catalyst were time-measured to see the light off. The stationary warm operation was prolonged until 20 min to get enough mass on the measuring filters for the analytics of PAH and SOF/INSOF.

After measurement of a given configuration there was a change of the configuration (oil, fuel, catalyst), a conditioning period of about 10 min and cooling down with blower during at least 30 min.

Table 2 shows all performed measuring series, which are called with "T" for TSDI and with "C" for Carburetor.

Used lube Oils and Fuels

The data of used lube oils with decreasing sulfur content are represented in Table 3.



*) from tailpipe to the sampling in the CVS-tunnel — TC…Thermo-Conditionner; TD…Thermo-Desorber

Figure 2. Sampling and measuring set-up for nanoparticulates analysis of the scooters with different variants of sampling methods.

Table 2. Measurements of scooter Peugeot TSDI and Carburetor with nanoparticle analysis; original catalyst and original oil dosage.

name	lube oil- type	lube oil- sulfur	fuel	Scooter
T11-T14	Panolin TS	S=6250 ppm	unleaded	TSDI
T21-T22	Panolin Synth	S=450 ppm	unleaded	TSDI
T31	Nycolube	S=350 ppm	unleaded	TSDI
T41-T42	Panolin Synth Aqua	S=0 ppm	unleaded	TSDI
T51-T54	Panolin TS	S=6250 ppm	Aspen	TSDI
T61-T62	Panolin Synth	S=450 ppm	Aspen	TSDI
T71	Nycolube	S=350 ppm	Aspen	TSDI
T81-T82	Panolin Synth Aqua	S=0 ppm	Aspen	TSDI
C11-C14	Panolin TS	S=6250 ppm	unleaded	Carburetor
C21-C22	Panolin Synth	S=450 ppm	unleaded	Carburetor
C31	Nycolube	S=350 ppm	unleaded	Carburetor
C41-C42	Panolin Synth Aqua	S=0 ppm	unleaded	Carburetor
C51-C54	Panolin TS	S=6250 ppm	Aspen	Carburetor
C61-C62	Panolin Synth	S=450 ppm	Aspen	Carburetor
C71	Nycolube	S=350 ppm	Aspen	Carburetor
C81-C82	Panolin Synth Aqua	S=0 ppm	Aspen	Carburetor

The oils: "Panolin TS & Nycolube" are semi-synthetic.

Two fuels were used during the measurements: standard market gasoline and an Aspen gasoline, which is almost aromats-free (aromats < 0,1 Vol %, benzol < 0,01 Vol %). The sulfur content of both gasolines was analysed and no sulfur was found.

5. RESULTS

5.1. Thermoconditioning of Sample for NP-Analysis

Several variants of sampling, according to Figure 2, were investigated and the results will be reported separately.

In the present paper the following examples of thermograms at tailpipe shall signalize, how the different engine technologies influence the composition and behaviour of the exhaust aerosol.

This part of research was performed at stationary warm operating condition of engine and catalyst and at maximum speed 45 km/h.

Figure 3 shows the results with Peugeot TSDI, sampling at tailpipe with minidiluter (MD) and thermoconditioner (TC, ThC).

Increased sample temperature in the TC provokes evaporation from the surface of particles and moves the SMPS PSD-spectrum to the lower peak-concentrations and smaller median diameters i.e. from the accumulation to the nuclei mode.

In the logarithmic scale a bimodality of the spectra with higher TC-temperatures is visible. This suggests that the particles in accumulation mode (60–90 nm), which remain at highest temperature are either very heavy compounds, or solids. These solids may have been formed already during combustion in the engine, similar to processes known from 4-stroke gasoline DI engines.

The NanoMet signals, Figure 4, confirm the tendency of increased solid particle ratio showing a decreasing amount of condensates (DC) and increasing amount of

Table 3. Data of the used lube oils.

Property	Unit	Panolin TS	Panolin 2-S Synth.	Panolin Synth. Aqua	Nycolube
Viscosity kin 40°C	mm^2/s	90	103	95	
Viscosity kin 100°C	mm^2/s	11.2	8.2	6.3	7.9
Density 15°C	kg/m^3	882	925	946	
Pourpoint	°C	–27	–40	–28	
Flashpoint	°C	>150	>150	>150	
Total Base Number TBN	mg KOH/g	3	3	2.5	
Sulfur	ppm	6250	450	0	350
Fe	ppm	0	5	2	1
Mo	ppm	1	0	0	0
Mg	ppm	2	3	1	2
Zn	ppm	105	18	0	0
Ca	ppm	617	458	11	322
P	ppm	90	36	16	6

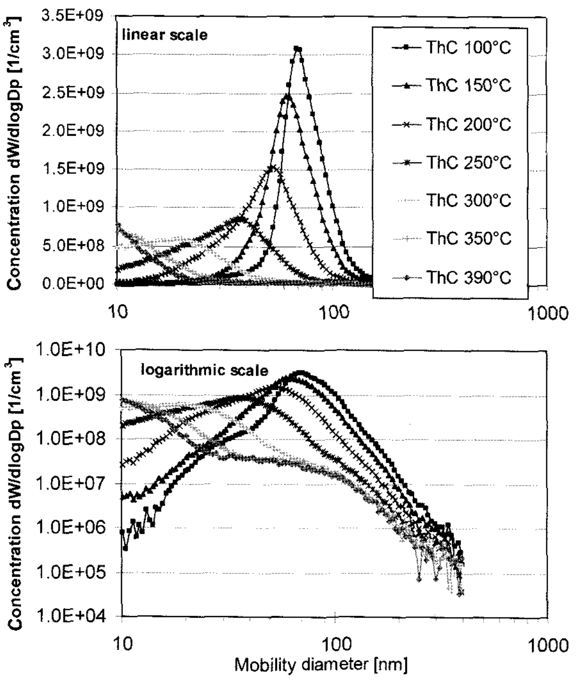


Figure 3. SMPS size spectra with thermo-conditioning of sample.

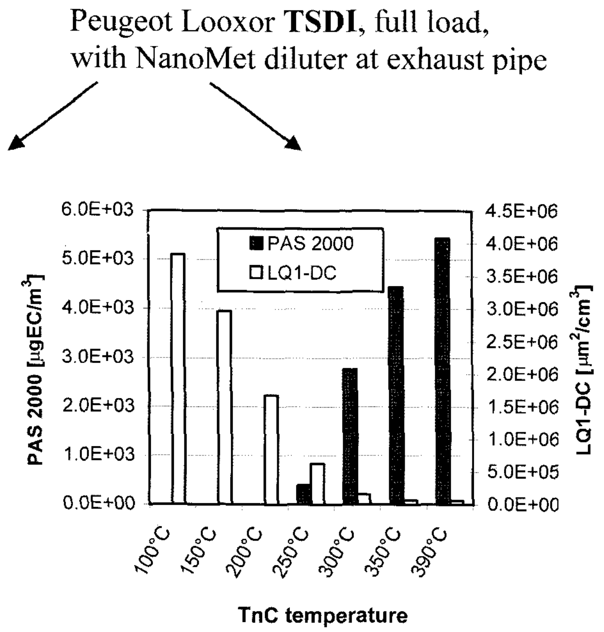


Figure 4. NanoMet signals with thermo-conditioning of sample.

carbonaceous surface (PAS) with the higher sample temperature.

PAS (photoelectric aerosol sensor) is sensitive to the surface of particulates and to the chemical properties of the surface. It indicates the solid particles.

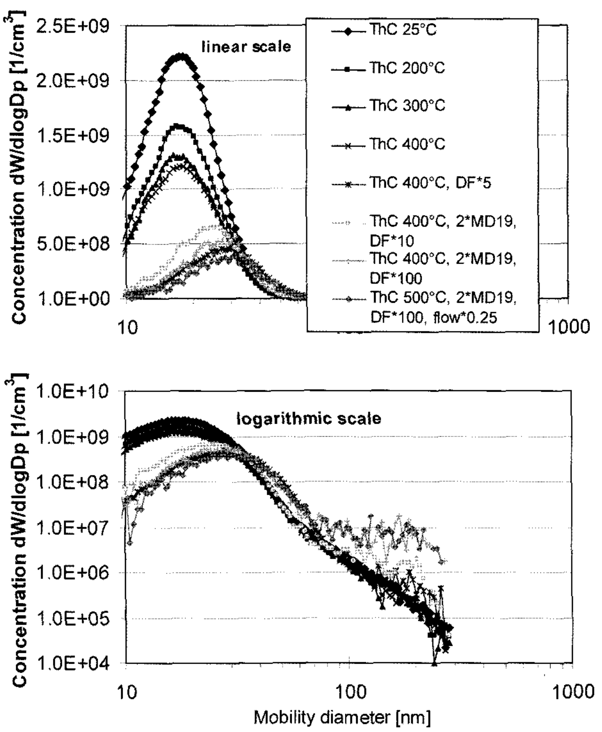


Figure 5. SMPS size spectra with thermo-conditioning of sample.

DC (diffusion charging sensor) measures the total particle surface independent of the chemical properties. It indicates the solids and the condensates.

The research of sampling at tailpipe with MD + TC for the Peugeot Carburetor is depicted in Figure 5. With increasing of the TC-temperature the very high count concentrations in nuclei mode decrease and with application of stronger dilution (5x, 10x, or 100x by mean of a second MD inline with the first one) it is possible to cut a part of this nuclei mode. This behavior of the aerosol from "Carb." is quite different form the one of TSDI (Figure 3). The Carburetor-version has a much higher exhaust gas temperature, which enables the creation of sulfates. The exhaust gas temperature of the TSDI is below the range of intensified sulfate production (oxidation SO_2 to SO_3).

Due to the higher exhaust gas temperature and the applied SAS (secondary air system) in the Carb.-version the oxidation of HC in the oxidation catalyst is more intense and the composition of aerosol is different than for TSDI.

The NanoMet data, Figure 6, confirm this fact showing almost unchanged DC and no PAS with increasing temperature (compare Figure 4 and Figure 6).

Generally it can be stated, that the sampling procedure: conditioning of the sample gas probe, dilution and sampling position have influence on the measured aerosol

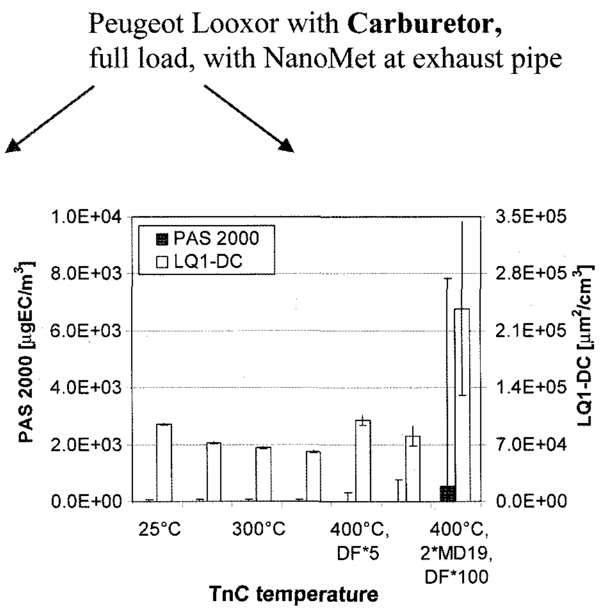


Figure 6. NanoMet signals with thermo-conditioning of sample.

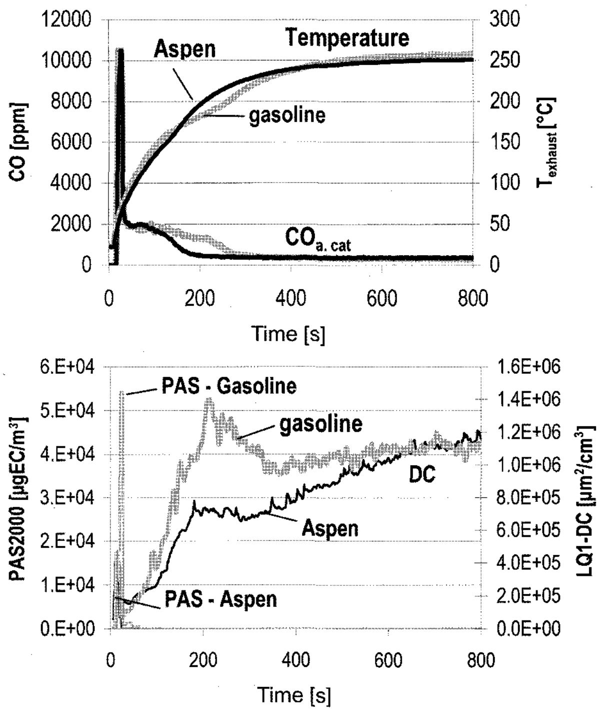


Figure 7. Cold start-acceleration-40 km/h with Gasoline-Aspen, Peugeot TSDI Carb., oil: Panolin TS.

characteristics (PM, PSD, PAS, DC).

5.2. Different Scooters, Oils and Fuels

The comparisons: gasoline-Aspen with NanoMet for

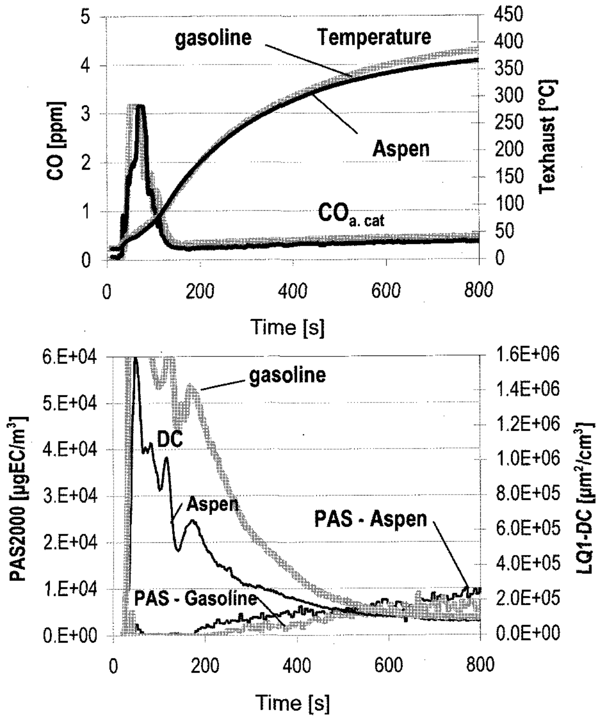


Figure 8. Cold start-acceleration-40 km/h with: Gasoline-Aspen, Peugeot Carb., oil : Panolin TS.

both scooters, Figure 7 and Figure 8, show a quicker light off of the catalyst and a lower total particle surface (DC) at cold start with Aspen.

Note that the light off for Carb.-scooter starts already below 100°C and t_{exh} reaches 380°C, while for TSDI the light off takes place at temperatures above 160°C and t_{exh} reaches 260°C, (t_{exh} measured approx. 40 cm after catalyst).

Due to these differences the NanoMet signals show quite different behaviour at warm operation, p. ex. after 10 min:

For TSDI, which has: lower t_{exh}, leaner tuning of the mixture and less postoxidation in the oxicat, the DC-signal indicates the presence of condensates and no solids are visible (PAS=zero), because if there are any of them, they are enveloped with the condensates. For Carburetor, which has: higher t_{exh}, richer tuning of the mixture and a very intense postoxidation in the catalyst, the solids appear (PAS increase) after the light off and during the warm-up of the catalyst. Simultaneously the condensates (DC) decrease very much because of the oxidation of VOC and because of deposition on the bigger solid particles. The solids originate from the rich combustion, but they can be also products of the strong postoxidation.

Following figures represent the influences of different oils on the particle emission metrics for both scooters and both fuels.

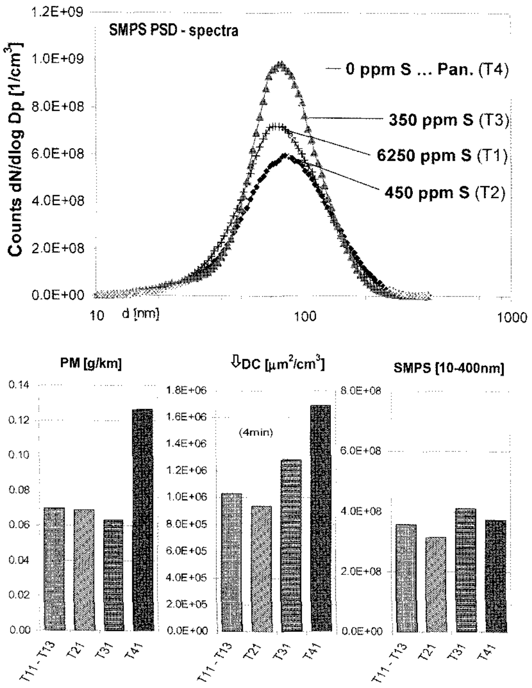


Figure 9. Particle mass and nanoparticles at 40 km/h warm with gasoline and different lube oils, Peugeot Looxor TSDI.

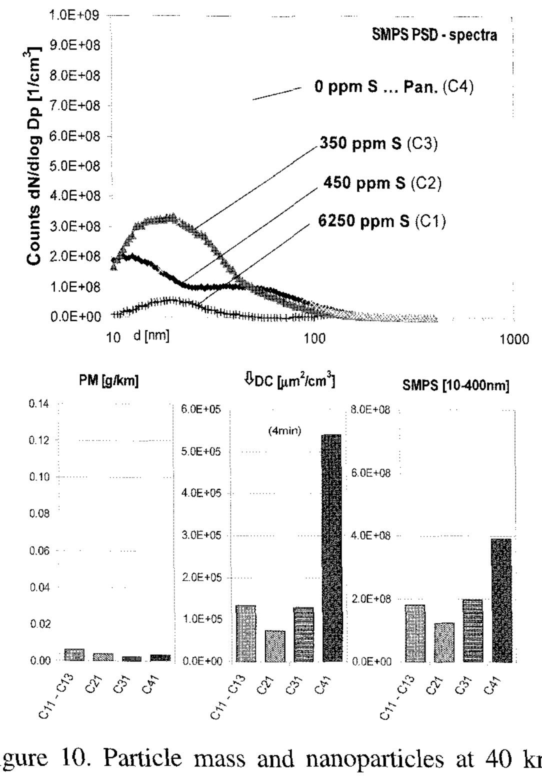


Figure 10. Particle mass and nanoparticles at 40 km/h warm with gasoline and different lube oils, Peugeot Looxor Carb.

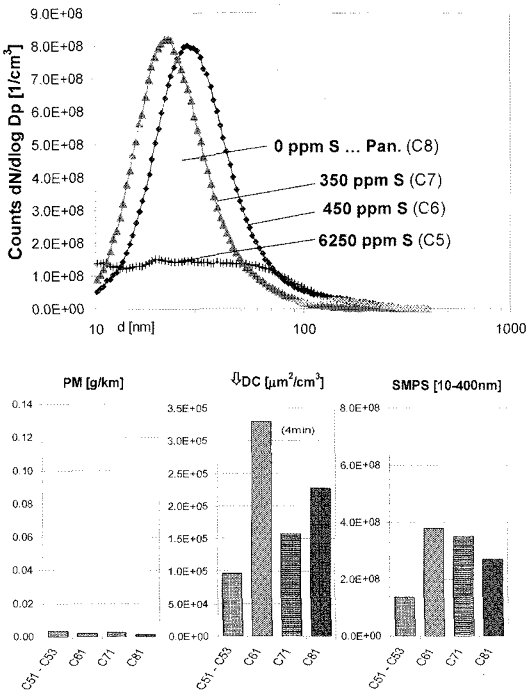


Figure 11. Particle mass and nanoparticles at 40 km/h warm with Aspen and different lube oils, Peugeot Looxor Carb.

For TSDI and gasoline the tendency is similar as in the previous research, Figure 9 – the oil with 0 ppm S has the highest PM- and DC-emission. The integrated SMPS particle numbers don't show this difference because of other PSD-shape for this oil T4.

For Carburetor there are generally much lower values of all represented emission parameters. This is due to the intense postoxidation with SAS and high t_{exh}. With gasoline, Figure 10, the bimodality of SMPS spectra caused by the sulfates is visible. The oil C4 with 0 ppm S has quite other nuclei mode, caused by other substances (ev. components of additive package). Given that DC is also maximal with this oil, the presence of organic condensates must be assumed.

Regarding influence of Aspen, Figure 11, can be remarked, that oil C8 (0 ppm S) moves the nuclei mode to lower sizes and lower amplitude – this is the result of coinfluence of the HC from fuel and HC from oil during the processes of combustion and postoxidation.

With the same reasons the changes for other oils (C6 and C7) can be explained, of course with addition of sulfates ($S \neq 0$).

6. CONCLUSIONS

Following conclusions can be pointed out:

(1) The composition of emitted aerosol depends on

engine technology (DI-Carb.), exhaust gas after-treatment (t_{exh}, SAS) and the used oil and fuel. The differences of the aerosol are visible by thermo-conditioning of the sample,

(2) The influences of lube oils on the particle emissions from previous works could be confirmed on the scooter with DI and gasoline and they are slightly modified on the Carb. scooter,

(3) Changing the fuel quality (Aspen) may increase the condensates with one oil and lower the condensates with another oil,

(4) Due to an intense oxidation in the exhaust of the Carb. scooter the particle mass emission PM is very little and it is almost independent on lube oil quality,

(5) Due to a high exhaust temperature of the Carb. scooter there are sulfates as condensates in the nuclei mode of the PSD-spectra,

(6) There is a clear evidence of coinfluences of oil & fuel on the spontaneous condensation and on the particle emission parameters,

(7) The sampling procedure: conditioning of the sample gas probe, dilution and sampling position have influence on the measured aerosol characteristics (PM, PSD, PAS, DC).

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