Abstract
The progressing exhaust gas legislation for on- and off-road vehicles includes gradually the nanoparticle count limits. The invisible nanoparticles from different emission sources penetrate like a gas into the living organisms and may cause several health hazards.

The present paper shows some results of a modern chain saw with & without oxidation catalyst, with Alkylate fuel and with different lube oils. The measurements focused specially on particulate emissions. Particulates were analysed by means of gravimetry (PM) and granulometry SMPS (PN). In this way the reduction potentials with application of the best materials (fuel, lube oil, ox-cat.) were indicated.

It has been shown that the particle mass (PM) and the particle numbers (PN), which both consisting almost exclusively of unburned lube-oil, can attain quite high values, but can be influenced by the lube oil quality and can be considerably reduced with an oxidation catalyst.

Introduction & Objectives
Small 2-stroke SI engine is the most important power unit for handheld machines, which require high power to weight ratio. There are continuous efforts to improve the handheld machines from the points of view of power, weight, fuel consumption and emissions.

To mention are the research works on: injection, mixture preparation and combustion, [1, 2, 3]; ignition, [4]; alternative fuels, [5] and some previous fundamental research efforts from Graz University of Technology (GUT) and AVL, [6, 7, 8, 9].

The problematic of emissions is well known: the lost oil lubrication and the scavenging losses of a part of fresh mixture result in heavy HC-emissions and also significant particle mass (PM)-, and particle number (PN)-emissions.

Several research works about the particulate matter (PM) have been performed by the small 2-stroke manufacturers. The actual state of knowledge can be summarized as follows, [10], [11], [12], [13], [14]:

• about 98% of the particulate mass (PM) consists of the lube-oil residues (SOF),
• the 2-stroke emissions and particulate matter (PM) have a mutagenous potential,
• PM can be reduced roughly proportionally with the reduction of the lube-oil ratio,
• PM depends on air-fuel-ratio, it is increased with the richer mixture,
• PM can be influenced to a limited extend by the fuel quality,
• oxidation catalyst can reduce PM of about 40 to 70% - this oxidation can be improved by the secondary air introduction in the exhaust pipe.
Some examples of NP-emissions of a chainsaw were given in [15]. It was found, that the higher oil treatment increases NP-counts, using alkylate fuel mostly reduces NP-counts and richer mixture with tendency moves the particle size distribution (PSD) to the lower particle sizes.

A considerable research of emissions of handheld equipment was performed in 2013 by AECC & GUT, [16]. Measurements of PM, PN and analysis of PM-residuum were included in the tests. It was demonstrated among others:

- PM- & PN-values for small SI 2-strokers are quite high (in the range of non-treated Diesel exhaust), but for a small 4-stroke engine with mixture-lubrication these emissions are at the same level,
- in one example: the oil quality influences the PM-emission (synthetic oil 50% lower PM), but has no impact on PN-level,
- at full load operation (WOT) the portion of EC measured with TGA is for all mixture-lubricated machines lower than 10%.

In the last decade the authors performed several basic investigations of NP from 2-S scooters with different technology (DI & carburetor), different lube oils and fuels, [17, 18, 19]. It was confirmed, that different lube oils produce different shapes of PSD’s which is connected with their chemistry. The oxidation catalyst together with a secondary air system oxidizes strongly the PM. It reduces from the nanoaerosol the accumulation mode, but simultaneously it increases the nuclei mode, so that the average particle counts stay nearly unchanged. The analysis of PM-residue showed, that mostly SOF is oxidized and the share of INOF in the strongly reduced PM increases.

Summarizing it can be stated, that the emissions of PM can be clearly reduced with the combination of different known technical measures.

The objectives of these investigations are to demonstrate the influences of different lube oil qualities on particulate emissions of a modern chainsaw with and without oxidation catalyst. The oil treatment is 2% and the used fuel alkylate, a best option to minimize the emissions.

The results will contribute to the further discussions about: what are the useful and feasible measures to attain further improvements?

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**Experimental Set-Up**

**Engine**

The engine used for the experiments was a series-manufactured 2-stroke SI engine with carburetor. The most important data of the engine are summarized in Table 1:

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>V14.223 2T fully synthetic no. 1</th>
<th>V14.224 2T fully synthetic no. 2</th>
<th>V14.225 2T fully synthetic no. 3</th>
<th>SAE50 LT no. 4</th>
</tr>
</thead>
<tbody>
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<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
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<td>Carburetor</td>
<td>Carburetor</td>
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</tr>
<tr>
<td>Mixture tuning</td>
<td>%</td>
<td>5%</td>
<td>5%</td>
<td>5%</td>
<td>5%</td>
</tr>
</tbody>
</table>

**Used Lube Oils and Fuels**

The data of used lube oils are represented in Table 2.

These lube oils have different content of ashes and different HC-compositions:

- Oil no 1 is mineral, with higher ratio of solvent and polymers,
- Oil no 2 is based on synthetic oil, with higher ratio of solvent and polymers,
- Oil no 3 is purely synthetic, without solvent and small ratio of polymers.

The ash-free oil no. 3 is considered to cause the lowest potential of metal oxides nanoparticles. The oil no. 4 an older type lower tier (LT) oil can be regarded as a worst case, concerning sulfur and metal content.

Two fuels were used during the measurements: Alkylate fuel (Aspen gasoline), which is almost aromats-free (aromats < 0,1 Vol %, benzol < 0,01 Vol %), [15] and standard market gasoline. The sulfur content of both gasolines was analysed and no sulfur was found.

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1. Abbreviations see at the end of this paper
Standard Equipment

Figure 1 shows a scheme of the experimental set-up and the measured parameters of the tested chainsaw.

Most important equipment was:

- eddy current dynamometer Vibro-Meter 2 WB 65-F (12 kW, 30'000 rpm)
- test bed Vibro-Meter with a control unit DCU 286 / 01 / KB
- fuel consumption volumetric
- dilution tunnel with nozzle-flow-meter
- pressure sensors
- temperature sensors (including spark plug)
- original silencer

For the measurement of gaseous emissions were used:

- sampling diluted / undiluted
- Horiba Mexa 9200
  for CO, CO₂, H₄CᵢR: AIA-120,
  for O₂: MPA 120,
  for NO, NO₂: CLA-150, nonheated line,
- H₄CᵢD: FIA 120

A direct measurement of the intake air flow is not possible without influencing the engine power. The air flow results indirectly from the measurements of fuel consumption, diluted exhaust gas flow and the dilution factor (CO₂ low/high). The dilution factor in the tunnel was between 20 at FL and 100 at idling.

In addition to that the air excess factor λ was calculated from the emission parameters according to several formulas.

The accuracy of assessment of air flow and of air excess factor is 6% to 8%.

The gas sample for gravimetry (PM), as well as for the particles size distribution (PSD, PN) is branched from the dilution tunnel.

Particulate Emissions Analysis

Following methods of analysis of the particulate emissions were used:

- gravimetric measurement of the particulate mass PM with the same method as prescribed for diesel engines (sampling temperature for PM was in present tests at 30°C, on Pallflex filters, own sampling & dilution system),
- analysis of particle size distribution (PSD),

Particle Size Analysis

The particle size and counts distributions were analyzed with following apparatus:

- SMPS - Scanning Mobility Particle Sizer, TSI (DMA TSI 3081, CPC TSI 3772)
- MD19 tunable minidiluter (Matter Eng. MD19-2E), heated to 150°C
- Thermoconditioner (TC) heated to 300°C

SMPS enables to count nanoparticles (NP) according to their size distribution (10-400nm).

The nanoparticulates measurements in this research program were performed at stationary engine operation (SMPS).

Test Procedure

Measurements were performed with and without oxidation catalyst with three different lube oils. The fuel was alkylate and the used oil rate was 2%. One of the oil variants without catalyst was also measured with the standard market gasoline.

For one of the variants the nanoparticles were measured also without thermoconditioner (TC, 300°C).

The operating points of the engine were responding to the 2-pt-test of the G3-cycle of the Directive 2002/88/EC (ISO 8178 G3) low idling and full load @ rated speed.
All measurements were performed at nearly the same ambient conditions with a warm engine (control of the spark plug temperature). For full load measurements the machine was operated 4 min (with 3 min SMPS-scanning); afterwards 30-60s idling and further repetitions of FL.

The engine speed at idling fluctuated between 1900 & 2100 rpm and the SMPS-scans were performed in intervals of 5 min.

Results

Without Oxidation Catalyst

Fig. 3 compares the particle size distributions (PSD) at idling and at 9000 rpm/full load (FL) with the ash-free lube oil no. 3.

At FL there are very high NP-concentrations in the nuclei mode with a maximum by equivalent diameters of c.a. 13 nm.

At idling the maximum of PSD is moved to bigger sizes (c.a. 30 nm) and lower count concentrations.

These differences can be explained with the conditions of the aerosol in the exhaust- and dilution system: the temperatures in undiluted exhaust are at FL by 500°C and at idling approximately 150°C. This means that only the heaviest hydrocarbons create the spontaneous condensates at FL, while at idling also the lower-boiling HC’s can condensate and contribute to the growth and agglomeration processes, before being diluted. These condensates cannot be removed by the thermoconditioner.

With this ash-free lube oil it can be supposed that there are no metal-, or metal oxides nanoparticles, which would contribute to the count concentrations, or seeding effects in nuclei mode.

An experiment of switching off the thermoconditioner (TC) at FL was performed and the result is represented in Fig. 4. Without TC - an evaporation tube heated to 300°C - there is condensation of HC, which promotes the growth and agglomeration of nanoparticles and moves the PSD to the bigger particle sizes.

Fig. 5 shows the comparison of NP-results at FL with three lube oils. The differences of particle counts (PC) are not very big and not always in the expected tendency: oil no. 3 (ash-free) causes mostly the lowest PC’s, oil no. 2 has the highest PC’s and oil no. 1 (highest ash content) has the results near to the oil no. 3.

Except of the differences of metal- and ash content the oils have different HC-compositions. This is an important factor influencing the condensation effects, depending on temperature, residence time and dilution ratio.
For oil no. 1 (with highest ash content) there is a surprising effect of lowering the PC's in the size range 10 nm (or below, as extrapolated). It can be supposed, that the present ashes (additive package) contribute more to the oxidation of the heavy precursors of the NP's in this size range, than to the particle number caused by their presence.

The last effect of lowering PC's below 10 nm with oil no. 1. Is also visible at idling, Fig. 6. Except of that there is no difference of PSD's or of integrated NP-counts for these three oils.

Figures 7 & 8 represent the comparison of results with Aspen and with gasoline. With a changed fuel the resulting matrix of unburned hydrocarbons is modified even with the same lube oil. This provokes slight differences of PSD's and of integrated particle counts. These differences are small.

**LT Lube Oil**

The different ash content of the modern, high-quality lube oils 1, 2, 3 did not show any clear and monotonous influence on NP. In particular the absence of ashes did not result in an extreme lowering of PC's in nuclei mode, which means that the effects of SOF-condensation and SOF-matrix are of major importance.

To create an example, an older type of lube oil was applied for comparison - a lower tier (LT) oil no. 4. Fig. 9 shows the comparison of PSD's with this oil no. 4 and oil no. 3 at FL in logarithmic and in linear scale.

Considering the sulfur and metal contents the oil no. 4 can be regarded as a worst and oil no. 3 as a best case. Oil 4 causes a higher level of PC-concentrations with both used fuels.
Alkylate (Aspen) and gasoline. There are also certain differences of results with both fuels, which confirm the previous observations (for Figures 7 & 8).

At idling, Fig. 10, some relationships are inverted: oil 3 shows the lowest PC's; only in the lowest size range (12-20 nm) and in the higher size range (40-120 nm) it shows the highest PC's; with oil 4 "gasoline" there are higher PC-values in nuclei mode, than with "Aspen".

It can be summarized that the LT lube oil increases clearly the PC-concentrations at FL, but is has less or no clear influences at idling.

Generally the condensation effects i.e. boiling behavior of the HC-components have a great impact on the results. Nevertheless the exact HC-compositions of the lube oils in this work were not known.

**With Oxidation Catalyst**

Test series were also performed with oxidation catalyst, which was included in the specific muffler by the original manufacturer and the mufflers (with/without ox. cat.) were exchanged on the same machine.

The geometrical shape of the muffler with catalytic coating was different from the non-coated one. The specific data of the coating were not available. The catalyst was new.

Fig. 11 shows an example of results with the best case "Aspen & ash-free oil no. 3": at FL there is a clear reduction of PC's with catalyst, this especially in the lowest size range (nuclei mode), below 30 nm. The measured exhaust gas temperatures were: without catalyst 433°C and with catalyst 505°C.

At idling, with exhaust temperatures below catalyst light-off, there are no clear influences to be noticed.

Fig. 12 summarizes the particle mass (PM) at FL, with & without oxidation catalyst.

The tests with oil no 4 were performed only without catalyst. The PM-result with this oil is in the same magnitude, like PM from oil no. 3 (ash-free), which means, that the metal- (ash-) content of the lube oil does not increase the particle mass.

A part of the metals or metal oxides from additive package of the lube oil is deposited in the nanoparticles. It is possible that these metal particles can serve as condensation kernels for SOF in certain conditions. All those effects are not visible in the PM-results of oils no. 3 & 4 at FL, which means that the major influence on PM-production is originating from the HC-matrix and from the processes of spontaneous condensation of heavy SOF.

Regarding the PM-values with oils 2 & 1 (w/o ox. cat.), which show that with increasing ash content the PM decreases, it must be supposed, beside the different HC-matrix of both oils, that the ash content helps to oxidize the lube oil during the combustion and contributes to lower PM. The oxidation catalyst reduces significantly the PM at FL.

The accuracy of assessment of the particle mass (PM) with the present installation is +/- 10%.
Fig. 13 shows the reduction rates of gaseous and of particulate emissions with the oxidation catalyst with three high quality lube oils. There is a significant reduction of PM & PN at FL: in average $K_{PM} \approx 95\%$ and $K_{PN} \approx 98\%$. There is also a significant reduction of gaseous components CO, HC & NO$_x$.

The reduction of NO$_x$ can be explained with the impact of the changed muffler (with the ox. cat.) on the pressure waves in the engine exhaust system - so called gas dynamic effects. Due to that the residual gas content (internal EGR) increases and the NO$_x$-emission decreases.

Another effect can originate from the non-selective catalytic NO$_x$-reduction, which is possible at reach operation with certain composition of catalyst coating.

It has to be remarked, that the absolute values of NO$_x$ are for such 2S-engines quite low (here at Fl w/o ox. cat. 70 ppm) and the relative reduction rates have less significance than for the other higher emission components.

At idling there also are reductions of the emission components in spite of the “cold” catalyst. These reduction rates are much lower.

Exception is with CO, which is increased with the oxidation catalyst. This can again be an effect of the modified gas exchange and most probably increased residual gas content of the engine, together with the partial oxidation of HC (scavenging losses), which arrive as pulses on the cooler catalyst.

In summary the catalyst shows very positive influences on the emissions results.

**Conclusions**

Following statements resulting from the present research can be remarked:

- the aerosol of the small mixture-lubricated 2-S engine consists mostly of SOF originating from lube oil,
- the effects of condensation are strongly influencing the resulting NP-concentrations and the heavy SOF-condensates cannot be eliminated by the thermoconditioner,
- the PSD's with three modern lube oils are similar and there is only a little effect of ash-free oil on the NP-concentrations,
- the use of lower tier lube oil with much higher metal- and sulfur content causes a higher NP-concentration level at full load; at idling there is no clear influence,
- the change of fuel Alkylate-gasoline is visible as small differences of PSD's due to the modified HC-matrix in exhaust,
- at full load the oxidation catalyst reduces significantly the NP-concentrations (up to 98%) and the PM (up to 95%),
- the higher ash content of the lube oil shows a tendency of reducing the PM-emissions (without catalyst).

**References**


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Definitions/Abbreviations

AECC - Association for Emissions Control by Catalyst
AFHB - Abgasprüfstelle der Berner Fachhochschule, Biel CH
AVL - Anstalt Verbrennungsmotoren
BAT - best available technology
BAFU - Bundesamt für Umwelt, (see FOEN), Bern CH.
CARB - Californian Air Resources Board
CPC - condensation particle counter
DI - direct injection
DMA - differential mobility analyzer
EC - elemental carbon
EGR - exhaust gas recirculation
EMPA - Eidgenössische Materialprüfungs- und Forschungsanstalt, Dübendorf CH
EPA - Environmental Protection Agency
ETHZ - Eidgenössische Technische Hochschule Zürich
FID - flame ionization detector
FL - full load
FOEN - Federal Office of Environment
GUT - Graz University of Technology
INSOF - insoluble fraction
IR - infrared
K - reduction rate of the component “x”
LT - lower tier
MD - minidiluter
NP - nanoparticles (here: in the SMPS measuring size range 10-400 nm)
OC - organic carbon
OP - operating point
PC - particle counts
PIB - Polyisobutylene
PM - particulate matter, particulate mass
PN - particles number
PSD - particles size distribution
SI - spark ignition
SMPS - scanning mobility particles sizer
SOF - soluble organic fraction
TC - thermoconditioner
TGA - thermogravimetric analysis
TTM - Technik Thermische Maschinen, Niederrohrdorf, CH
WOT - wide open throttle