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Detailed Characterization of Particulate Matter in Alcohol Exhaust Emissions

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ABSTRACT

A way to reduce net CO_2 emission and circumvent the high particle emissions from compression ignition (CI) engines, while retaining high efficiency, is by utilizing lighter alcohols in the partially premixed combustion (PPC) process. Methanol and ethanol have a very short carbon chain, and form less soot/particulate matter (PM) during combustion compared to diesel fuel. This study analyzes and compares the characteristics of PM emissions from methanol, ethanol and diesel in terms of soot mass concentration, number concentration and particle size distribution in one cylinder of a six cylinder Scania D13 heavy duty (HD) engine under two operating loads; 6 bar and 10 bar gross mean indicated effective pressure ($IMEP_G$). An electrostatic precipitator (ESP) was used to sample PM on copper grids for transmission electron microscopy (TEM) and energy dispersive X-ray analysis. Also, new and used lubrication oil together with methanol and diesel were analyzed for their sulphur and metal content.

Nucleation mode and the majority of accumulation mode particles from methanol and ethanol combustion, showed mainly Ca, S, P and Zn in the energy dispersive X-ray spectrometry (EDX) analysis and were hypothesized to be emitted mainly from the lubrication oil rather than the combustion of the fuel itself. From diesel combustion, the accumulation mode particles were more abundant in comparison with the alcohols and PM/soot emissions measured with the photo-acoustic technique were 3 to 10 times higher than for the alcohols. There were also fewer nucleation mode particles present; although they consisted of the same four abovementioned elements. Utilizing alcohols in CI engines have a great advantage regarding PM, particle number emissions and efficiency. However, the resulting nucleation mode particles need to be reduced to avoid future health concerns.

INTRODUCTION

Renewable fuels are currently being introduced to reduce net CO_2 emissions. Compression ignition (CI) engines provide high efficiency but as they cause elevated soot emissions they require expensive after treatment systems. Particulate matter (PM) emissions in the form of black carbon/soot are associated with adverse health effects and additionally warms the atmosphere due to their absorptive properties, referred to as short lived climate polluters.

Particle emissions from combustion engines furthermore cause adverse health effects by penetrating the cell membranes, entering the blood and finally reaching the brain [1]. Studies have shown that particulate matter can even induce inheritable mutations in mice [2].

The combustion engine, being a well-known source of aerosols, have seen some remarkable improvements regarding efficiency and emissions the last two decades. While the choices of combustion engines in the private sector stands mainly between the spark ignition (SI) and CI, the choice in the transport sector is limited to the heavy duty (HD) CI due to its high efficiency in combination with high torque rating. The drawback of the conventional CI engine is its requirement for a high cetane number fuel; diesel. Diesel is a fuel containing long carbon chained constituents, which forms PM when combusted in the conventional diesel combustion (CDC) process [3].

Alternative fuels can improve engine emissions. Several fatty acid methyl ester (FAME) fuels have been proven to reduce soot emissions in comparison to diesel fuel while being derived from biomass, lowering the net CO_2 emissions significantly [4][5][6]. Seemingly, in the operation conditions in which the diesel engines emit high amounts of soot, the reduction in PM when utilizing FAME in the CDC process is quite significant, but the tail-pipe soot concentration would still be above the EURO VI

PM legislative limits if no diesel particulate filter (DPF) is used. This is based on information obtained from particle size distribution measurements conducted for several fuels, including FAME and diesel [7].

However, recently the attention has been focused on the use of alcohols in the CDC process to reduce the PM emissions to ultralow levels; not needing exhaust after treatment systems (EATS) for particles. The alcohols used to achieve this are methanol and ethanol. Due to their molecular structure, they do not form intermediate precursors that favor soot production during the combustion process [8].

A former study was conducted, by the institutes involved in this work, measuring the PM from the PPC (Partially Premixed Combustion) and CDC process utilizing ethanol and methanol in a Scania D13 engine using no EATS. The larger accumulation mode was largely absent for the alcohol cases; a nucleation mode (<30 nm) totally dominated the particle size distribution [9].

Since then, further interest has been evoked regarding the characteristics of these nucleation mode particles. It is known that combustion engines, operating on diesel fuels, emit a high number of particles containing metal oxides most likely resulting from evaporation of material of lubrication oil, friction surfaces such as piston rings, cylinder liners, camshafts, crankshaft, valves etc. followed by nucleation and condensation [10]. The particles originating from lubrication oil are generally particles in the nanometer size, while particles from engine wear are in the micrometer size.

Until now, the characteristics of these nanometer sized particles originating from alcohol combustion in an engine are virtually unknown. It has been hypothesized that the PM emitted from alcohol combustion in the PPC and CDC process originated from lubrication oil and engine wear. During previous and ongoing measurements, motoring the engine resulted in emissions containing 20 nm particles in very high concentrations. The motivation of this work is to study the characteristics and effects of methanol and ethanol PM in more depth to understand the origins, formation and constituents. Characterizing these nucleation mode nanoparticle emissions is essential to assure that the introduction of new alternative fuels does not compromise health and climate aspects of the particulate emissions further.

In this work, the experimental setup is a single cylinder engine in which three fuels were tested. Two operation points were tested for every fuel while measuring soot mass concentration with an AVL MSS (Micro Soot Sensor). Particle number concentration and size distribution was measured using a Cambustion DMS500. An electrostatic precipitator (ESP) was used to sample particles on carbon coated copper grids for subsequent structure and elemental analysis with transmission electron microscopy (TEM) and energy dispersive X-ray (EDX) spectroscopy.

METHOD

FUELS AND OPERATION CONDITIONS

In this study, three different fuels were tested; methanol, ethanol and Swedish MK-1 diesel. It is worth noting that the alcohols used as fuels contained non-volatile impurities from the distillation process in trace amounts. To secure the safety of the engine's fuel delivery system, 200 ppm of Infineum R566 was added to the alcohols to increase their viscosity. Moreover, no additives were added to the MK-1 prior to utilization in the engine. The lubrication oil used is Statoil PowerWay GE40, a lubricant used mainly for gas engines. In Tab. 1 below, the specifications for the utilized fuels can be observed.

Furthermore, engine lubricant (used as well as unused), methanol blended with Infineum R566 and Swedish MK-1 were analyzed for their metal content to further investigate the origins of the emitted PM.

To avoid contamination of the exhaust manifold due to deposits, exhaust pipes and consequently the exhaust PM measurements, the methanol and ethanol experiments were conducted before the MK-1. Prior to the experiments, methanol was utilized at high engine load to try to burn off as much of the previously accumulated soot as possible.

Table 1. Fuel Specifications [11][12][13].

	MeOH	**EtOH**	**MK-1**
RON [-]	107-109	108-109	-
MON [-]	92	89	-
CN [-]	-	-	53-57
H/C [-]	4	3	1.8
O/C [-]	1	0.5	0
Q_{LHV} [MJ/kg]	19.9	26.7	43.2
$(A/F)_S$ [-]	6.47	9.00	14.5

All the tests were conducted at 1200 rpm and two loads; 6 bar and 10 bar gross mean indicated effective pressure ($IMEP_G$). The start of injection (SOI) was at all operation conditions set to keep a constant combustion phasing; CA50 at ~5 crank angle degrees after top dead center (CAD ATDC). The injection pressure was during all experiments set to 1200 bar. The intake temperature was set to 110 ^{0}C, high enough to make the alcohols auto ignite, while the heater was turned off when running MK-1 resulting in an intake temperature of ~30 ^{0}C. The results from the TEM analysis are exclusively from the engine operation conditions at $IMEP_G$ = 6 bar. Lambda, λ, was kept constant for each load; λ≈3.0 and λ≈1.9 at 6 bar and 10 bar $IMEP_G$ respectively.

ENGINE SETUP

The engine, on which the experiments were conducted is a six cylinder Scania D13 converted to run only on one cylinder. The specifications of the engine are given below, in Tab. 2.

Table 2. Engine specifications.

Displaced volume [cm^3]	2124
Stroke [mm]	160
Bore [mm]	130
Con. rod length [mm]	255
Compression ratio [-]	17.3:1
Number of valves [-]	4
Swirl ratio [-]	2.1
Exhaust valve open [-]	137° CAD ATDC
Inlet valve closing [-]	-141° CAD ATDC

Since the gas flow through a single cylinder is not adequate to run a turbocharger, pressurized air is supplied from an external compressor. Worth noting, is that the exhaust gas recirculation (EGR) valve was sealed to inhibit even the smallest leakage of EGR into the intake.

Because alcohols require a high intake temperature to ignite, a 7.5 kW heater is located between the fresh air supply and intake manifold. On the exhaust pipe of the setup, there is four sampling probes to the emission analyzers. The probes were positioned with the minimum distance away from each other to avoid measurement inaccuracy due to flow disturbances. The test rig is displayed in Fig. 1.

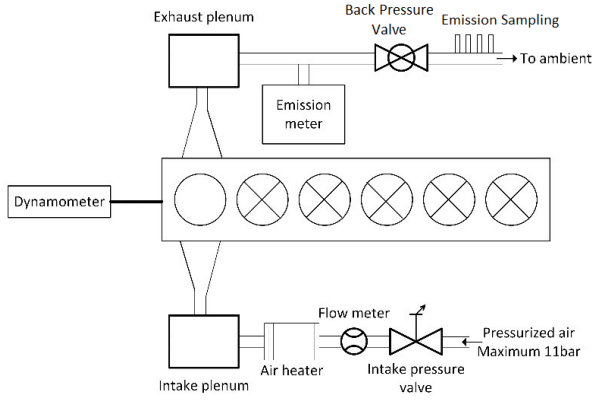

Figure 1. Schematic of engine setup [14].

EMISSION MEASUREMENT

During the experiments, several emission measurement systems were used to measure both the gaseous and aerosol particle emissions.

The constituents in the exhaust gas was measured using an AVL AMA i60 emission measurement system. An infrared detector (IRD) was used to measure the dry CO and CO_2 emissions. Wet NO_X and NO was measured by a chemiluminescence detector (CLD). The wet total hydrocarbons (THC) concentration was quantified using a flame ionization detector (FID). Moreover, the O_2 concentration was measured by a paramagnetic detector (PMD).

In the AVL micro soot sensor (MSS), a photoacoustic measurement technique is used to measure the equivalent Black Carbon (eBC) mass concentration, here denoted PM concentration. Using assumptions of particle mass absorption cross section the mass concentration is derived from the measured absorption of modulated light (808 nm wavelength). This light beam is directed toward the path of the diluted exhaust gas, which will make the carrier gas expand and contract due to the heating and cooling. During the carrier gas expansion and contraction, a sound wave is emitted. This sound wave is detected by sensitive microphones which translate it to a concentration of soot. The measurement range of the MSS is 0.001-1000 mg/m^3, and the sensitivity is in the level of 1 μg/m^3.

The DMS500 uses a technique in which the particles are positively charged using a corona charger. The charge that the particles receives is approximately proportional to their surface area. After being charged, the particles pass a strong radial electrical field and are deposited on different electrometer detectors depending on their electrical mobility. The current from the 22 electrometers are measured. Using the diesel inversion matrix during data processing, the signal is transformed into a number particle size distribution. This device measures particles in the range of ~5 nm to 1 μm with a maximum sampling rate of 10 Hz. Moreover, the DMS500 uses a cyclone right at the sampling probe to remove larger particles, followed by primary dilution of the exhaust gas with a ratio of 5:1. After the gas is passed through the heated line, further dilution is conducted depending on the operation condition.

While the AVL MSS and DMS500 sampled gas directly from the exhaust pipe, the exhaust gas sampling for the TEM grids was conducted at a 90° angle and diluted three times with 150 °C air using a Dekati ejector diluter and then passed through a quarter inch heated tube (300 °C) to remove condensed species. The dilution setup is illustrated below in Fig. 2.

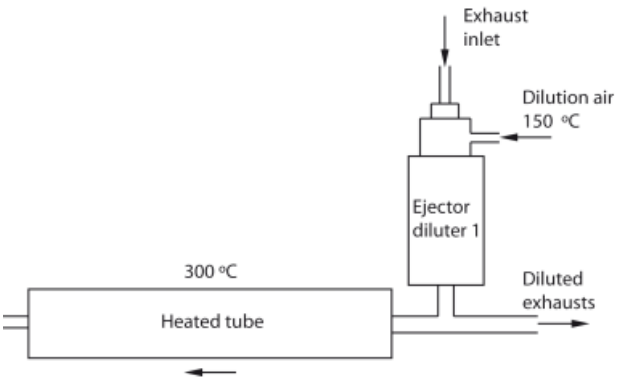

Figure 2. Schematic of the dilution setup. Diluted exhaust gas is expelled to the exhaust fan while the gas going through the heated tube passes to the ESP.

An ESP (NAS model 3089 TSI) was used to sample particles on carbon coated cupper grids. The grids used for the TEM analysis was Cu-400LD copper grids from Pacific Grid-Tech.

The electron microscope used to analyze the TEM grids was a JEOL 3000F. It is a high resolution TEM with a field emission electron source. It is equipped with a silicon drift detector (SDD) based EDX system and a 2x2 k charged coupled device (CCD) camera to record images.

RESULTS AND DISCUSSIONS

SOOT MASS CONCENTRATION

In Fig 3. below, the soot mass concentration from the AVL Micro Soot Sensor is given for each fuel. Methanol and ethanol emit very small amounts of soot while the soot emissions from Swedish MK-1 are three to four times higher, which was expected. From the data obtained from the AVL MSS, the specific soot mass concentration is calculated.

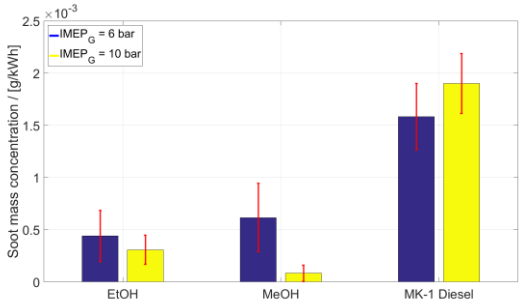

Figure 3. Specific soot mass concentration for the three fuels.

The increase in soot emissions with increasing load from Swedish MK-1 is due to the reduced λ when running at higher loads. The same trend has been shown in several studies for sooting fuels, including gasolines [15][16].

An earlier study showed that the difference in exhaust soot mass concentration between MK-1 and the alcohols becomes much more significant if the engine is operated at conditions which would reduce soot oxidation (late cycle soot removal), for example high levels of EGR, high intake temperature and low injection pressure. Soot mass concentrations never exceeds 0.01 g/kWh when running an engine using alcohols, while the MSS would easily measure 2 g/kWh from gasoline PPC with EGR utilization, and this figure is even higher for MK-1 combustion with EGR [9].

It should be noted that the error bars for the oxygenated fuels are very large in comparison to their mean value. This indicates that it is significantly harder to study a trend for alcohols than MK-1. Furthermore, it should be mentioned that the error bars are calculated using the following mathematical formula for standard deviation;

$$S = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left|A_i - \frac{1}{N}\sum_{i=1}^{N}A_i\right|^2}$$

where A_i is the elements of the vector containing the measurements from the AVL MSS and N is the total number of elements.

PARTICLE NUMBER SIZE DISTRIBUTION

In Fig. 4, Fig. 5 and Tab. 3, the particle size distribution and number concentration as well as the aerosol size distribution parameters can be observed for each fuel at the two tested loads. The fuel emitting the highest number concentration of particles is methanol followed by ethanol and MK-1 diesel. Similar results have been published previously showing that when the size distribution is dominated by nucleation mode nanoparticles, the total particle number (TPNC) is uncorrelated with soot mass emissions [9].

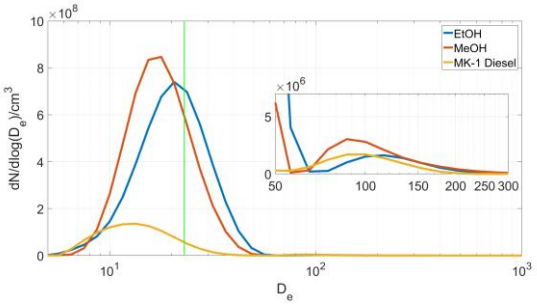

Figure 4. Particle size distribution for $IMEP_G$ = 6 bar. 23 nm marked by green line.

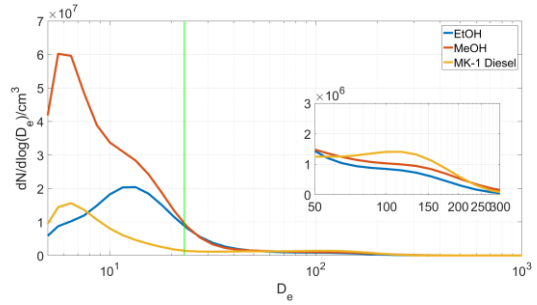

Figure 5. Particle size distribution for $IMEP_G$ = 10 bar. 23 nm marked by green line.

For all three fuels, the majority of the number of particles emitted are in the nucleation mode at both 6 bar and 10 bar $IMEP_G$. At higher load, the nucleation mode CMD (Count Mean Diameter) is reduced for all three fuels, while a slight increase can be seen in the accumulation mode region for MK-1 in relation to the alcohols. This increase in accumulation mode for MK-1 diesel is in-line with the slight increase in soot mass emissions that was observed.

When a stronger soot mode (accumulation mode) was present a decrease in the concentration in the nucleation mode was observed. This suggests that the nucleation mode particles rapidly coagulate with the larger soot agglomerates.

In Fig. 4 and 5, green vertical lines can be observed at 23 nm. In the EURO VI standard, there is a solid particle number (PN) limit at 8.0E11/kWh, and only particles larger than 23 nm are included in that PN due to the difficulties to determine whether the particles, smaller than this size, are solid or liquid. Tab. 3 gives the particle count median diameter (CMD), geometrical standard deviation (GSD) and total particles number concentration (TPN) for nucleation mode particles as well as accumulation mode particles.

Table 3. Aerosol size distribution parameters.

	EtOH 6 bar	EtOH 10 bar	MeOH 6 bar	MeOH 10 bar	MK-1 6 bar	MK-1 10 bar
CMD Nuc. [nm]	19.3	12.2	17.1	7.5	12.7	6.8
CMD Acc. [nm]	124.9	62.5	75.1	42.7	93.3	78.6
GSD Nuc. [-]	1.4	1.6	1.4	1.6	1.5	1.5
GSD Acc. [-]	1.4	1.9	1.6	1.9	1.4	1.9
PN Nuc. [#/kWh]	1.1e13	2.6e11	1.3e13	6.4e11	3.5e12	1.3e11
PN Acc. [#/kWh]	1.6e10	2.1e10	3.4e10	4.9e10	2.6e10	3.5e10
TPN [#/kWh]	1.1e13	2.8e11	1.3e13	6.3e11	3.4e12	1.6e11

EDX-TEM IMAGING - METHANOL AND ETHANOL

The TEM images reveal that the particle size distribution and morphology in the case of methanol and ethanol combustion are very similar. The particles found in the samples consisted of spherical nanoparticles in the size range of 5-50 nm as well as larger and more complex agglomerates. It was noted that the 5-50 nm sized particles consisted of one or more core, as seen in Fig. 6. These cores appear brighter on the images indicating that these regions are either hollow, liquid or consisting of lighter elements in comparison to the surrounding shell. However, based solely on these TEM images one cannot draw any clear conclusions regarding the phase or composition of these cores.

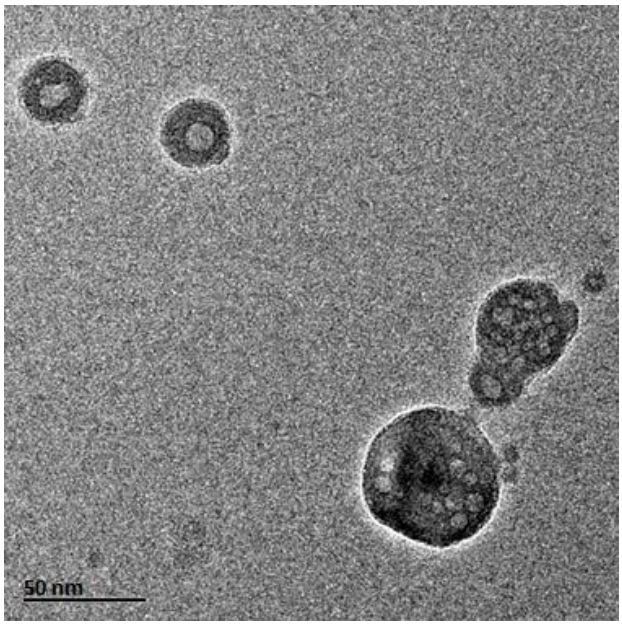

Figure 6. Spherical hollow nanoparticles emitted from ethanol

An important notation when looking at TEM images, is that the observed body is a three dimensional object seen from a two dimensional perspective.

Although less common, soot agglomerates were observed in the TEM grids. This confirms that the larger accumulation mode particles were soot particles. In a portion of the observed soot aggregates, there were smaller nanoparticles incorporated in the carbon structure. In Fig. 7 below, it is possible to see agglomerated particles both without (left) and with (right) the earlier seen cores. Particles emitted from alcohol combustion larger than 50 nm in diameter will most probably be one of the two abovementioned agglomerates.

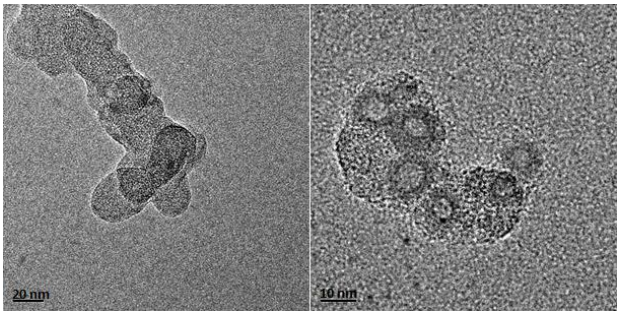

Figure 7. Ethanol combustion soot particle without incorporated nanoparticles (left) and a soot particle with incorporated hollow nanoparticles (right).

All the observed particles with a diameter below 50 nm consisted of the same chemical elements. From the EDX it was determined that the particles consisted of altering proportions of the following chemical elements; zink, calcium, sulphur and phosphor. It was therefore possible to rule out the possibility that these particles were primary (monomer) carbonaceous soot particles. The relative fraction of each element varied significantly from particle to particle. However, all particles consists of a minimum of 5 at.% of the abovementioned elements.

The results from the EDX analysis from a single particle with a diameter of ~25 nm is shown in Fig. 8. From Fig. 8 it can be seen that the peaks for zink, calcium, sulphur and phosphor are present. Additionally, there is oxygen, carbon, copper and silicon peaks present; however, these are artifacts from the grid as well as the detector and are not singly related to the particle. Results from the analysis of the lubricant showed that Zn, Ca, S and P are the most abundant additives.

It can also be mentioned that it was not possible to achieve a high enough resolution to differentiate between the core and the rest of the particle in the EDX.

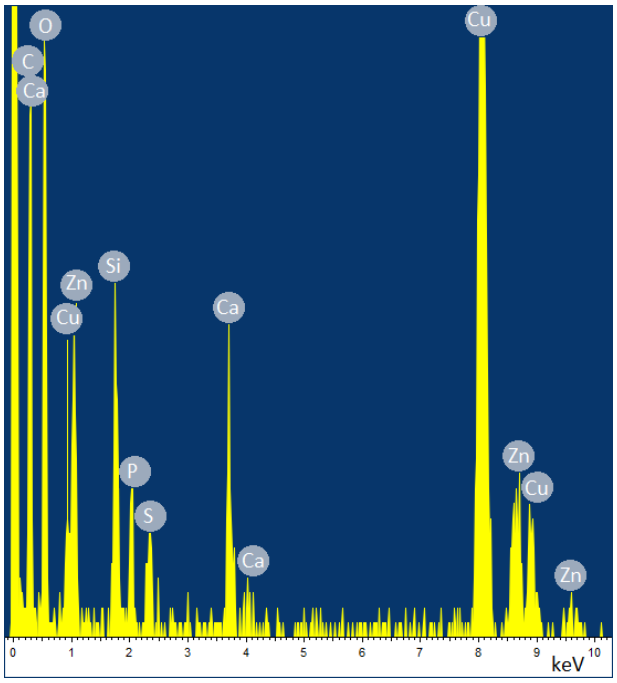

Figure 8. Results from the EDX analysis of a 25 nm nanoparticle.

If the nanoparticles originated from engine wear, mainly from the friction region between the piston rings and cylinder liner, they would result in a strong Fe peak in the EDX analysis, seen in Fig. 8. The Fe peak, however, was not present in the spectra and it can therefore be excluded that these particles derive from engine wear. Consequently, lubrication oil minerals are much stronger candidates for the origin of these nanoparticle emissions.

It is reasoned that the particles containing Fe will be absorbed into the oil film on the cylinder liner to later in the cycle be drawn back into the oil sump. This is backed up by the lubricant analysis results; used engine lubricant contained a higher concentration of Fe than the unused, 6 wt. ppm and 1 wt. ppm respectively. In earlier studies, it was shown that PM originating from engine wear was found to be in much lower quantity than PM originating from the lubrication oil. In addition, if engine wear PM were to be found on the TEM grids, these would be separate particles, which would be highly localized and not bound to any carbonaceous PM [17].

EDX-TEM IMAGING - DIESEL

As expected, the observed particles on TEM grids collected from diesel combustion were significantly different from those from alcohol combustion. The TEM analysis verified the results obtained from the Cambustion DMS500 and the AVL MSS, with numerous smaller nucleation mode particles and a low number of larger soot agglomerates. The particle emissions from alcohols and diesel combustion clearly differed with the alcohols emitting more nucleation mode particles, and diesel emitting more soot agglomerates.

This was also the case in the TEM images, were a higher amount of large agglomerates in comparison to the spherical smaller nanoparticles were observed in the diesel sample. In the alcohol samples these larger agglomerates were more rarely found. Fig. 9 shows a typical snapshot of the two different systems were it is possible to observe a higher amount of large agglomerates in the lower image in comparison to the upper.

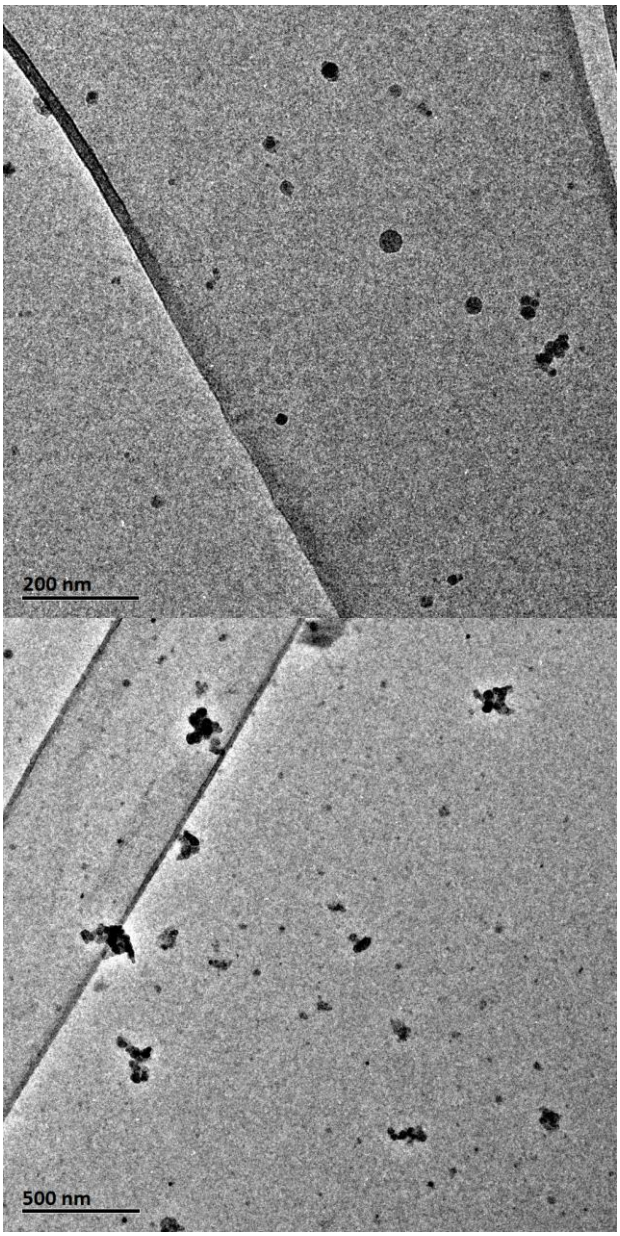

Figure 9. A comparison of the TEM grid from ethanol (upper image) and diesel (lower image).

The results from the EDX measurements were similar to those seen from methanol and ethanol, i.e. the particles also consist of Zn, Ca, S and P. Large carbonaceous agglomerates is relatively abundant on the diesel produced TEM grid. Such particles are less abundant on the alcohol TEM grid.

ORIGINS OF NANOPARTICLES

From the engine lubricant and fuel analysis, it can be concluded with high certainty that the lubricants used in the engine and fuels are the main source of the

nanoparticles emitted from alcohol combustion since the chemical constituents found in the PM emitted from alcohol is found typically in lubricants. First and foremost, is the engine oil which is lubricating, amongst other surfaces, the surface between the cylinder liner and piston skirt. The other lubricant, as mentioned above, is the Infineum R566, used in the alcohol fuels to reduce friction in the low and high pressure fuel pumps and other moving parts, such as the fuel injector. Infineum R566 is not a single chemical but a blend consisting of heavier esters and fatty acids and contains in itself up to 40 ppm sulphur, which could slightly contribute to the sulphur detected in the alcohol TEM grids and contribute to nucleation. However, when used in fuels in amounts of 300 ppm, the sulphur content of the fuel will increase with ~0.012 ppm, which is close to negligible when compared with the sulphur content of engine lubricant, consisting of ~0.66 wt.%. Worth noting is, that the content of Zn, P and Ca in methanol and diesel did not exceed 2 ppm, while the sulphur content was 0.011 wt.% for methanol and 0.010 wt.% for diesel.

When the piston is on its way down towards bottom dead center, a small amount of engine lubricant is left on the cylinder liner and a fraction of it is included in the combustion process due to the high combustion temperature. The added minerals in the lubricant will oxidize and then be expelled with the exhaust gases as metallic nanoparticles with a non-volatile core [18]. The accumulation mode particles observed on the alcohol TEM grids should in theory also originate from the utilized lubricants mentioned earlier. Another possible source of these particles could be the inside of the exhaust pipes, on which soot have accumulated during previous experiments, where the engine have been running on MK-1 and other long carbon chained fuels. Moreover, measurements with the DMS500 were conducted in the intake and exhaust while motoring the engine. On the exhaust side, the particle number concentration was in the order of ~10^8 #/cm^3 while significantly lower on the intake side; ~10^3 #/cm^3.

When running the engine on Swedish MK-1 diesel, the particles produced will have different origins. It is most likely that the nanoparticles will have their origins from the engine lubricant rather than the fuel itself. The accumulation mode particles, as those seen in Fig. 9 (lower image), will have originate from the fuel combustion. During the combustion, soot is formed and oxidized depending on the engine operation conditions, and is then expelled during the exhaust stroke. The accumulation mode particles from diesel combustion have experienced a higher degree of agglomeration (coagulation) as evidenced by their larger size.

SUMMARY AND CONCLUSIONS

The engine used in this work was a single cylinder D13 HD engine. Three fuels were tested; methanol, ethanol and MK-1. Each fuel were tested at two loads; 6 and 10 bar $IMEP_G$ while measuring soot mass concentration, particle size distribution and collecting exhaust samples onto carbon grids for TEM analysis. Based on this work, the following conclusions could be drawn:

1. For methanol and ethanol, higher load reduces the soot mass concentration. Other than this, there were no particular trend observed regarding soot mass concentration for methanol and ethanol.
2. The alcohols emitted a higher PN than MK-1 in the nucleation mode. Methanol emitted a higher PN than ethanol.
3. Increasing the load when utilizing any of the tested fuels will reduce the number of nucleation mode particles.
4. For the alcohols, varying the load did not affect the concentration of accumulation mode particles in the exhaust.
5. The TEM grid samples for methanol and ethanol are very similar.
6. The vast majority of the solid particles emitted from alcohol combustion had a circular cavity in the center.

It has been shown repeatedly how alcohols emit a higher number of nucleation mode particles compared to diesel exhaust. The absence, or low concentration, of larger soot particles during highly efficient combustion with either alcohols or diesel resulted in very high solid nanoparticle emissions with diameters from about 5-40 nm. These small nanoparticles were also found in large amounts sticking to the few existing soot particles (~100 nm). From these observations it is hypothesized that the nanoparticles are always produced in the engine, but are not detected as free particles due to rapid coagulation on soot agglomerates in less efficient, sooting combustion. From a health perspective nanoparticle emissions may be problematic because of their large surface area per unit mass they provide a higher deposition probability in the respiratory tract and higher risk of translocation within the body compared to larger particles [19].

In addition, we found that the nanoparticles were composed of Zn, Ca, S and P in various degrees. The toxicity of the nanoparticles will also depend on the chemical composition. For example, zinc oxide nanoparticles being cytotoxic substance, have shown to disrupt cellular Zn homeostasis and consequently leading to mitochondria damage and cell death [20].

Further studies on how to reduce the large emissions of nanoparticles found in this study and in previous studies, are clearly motivated by the possible health effects associated.

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NOMENCLATURE

λ: Lambda, $\left(\frac{A}{F}\right)/\left(\frac{A}{F}\right)_S$
ATDC: After Top Dead Center
CA50: The crank angle at which 50% of the charge has been consumed.
CAD: Crank Angle Degrees
CCD: Charge Coupled Device
CDC: Conventional Diesel Combustion
CI: Compression Ignition
CLD: Chemiluminescence detector
CMD: Count Mean Diameter
DPF: Diesel Particulate Filter
EATS: Exhaust After Treatment system
eBC: equivalent Black Carbon
EDX: Energy Dispersive X-ray
EGR: Exhaust Gas Recirculation
ESP: Electrostatic precipitator
FAME: Fatty Acid Methyl Ester
FID: Flame Ionization Detector
GSD: Geometric Standard Deviation
HD: Heavy Duty
IMEP$_G$: Gross indicated mean effective pressure
IRD: Infrared detector
MK-1: Environmental Class 1. Swedish pump diesel.
MSS: Micro Soot Sensor (AVL)
PM: Particulate Matter
PMD: Paramagnetic detector
PN: Particle Number
PPC: Partially Premixed Combustion
SI: Spark Ignition
SOI: Start Of Injection
TEM: Transmission Electron Microscopy
THC: Total hydrocarbons
TPN: Total Particle Number

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