

Exhaust PM Emissions Analysis of Alcohol Fueled Heavy-Duty Engine Utilizing PPC

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ABSTRACT

The focus has recently been directed towards the engine out soot from Diesel engines. Running an engine in PPC (Partially Premixed Combustion) mode has a proven tendency of reducing these emissions significantly. In addition to combustion strategy, several studies have suggested that using alcohol fuels aid in reducing soot emissions to ultra-low levels. This study analyzes and compares the characteristics of PM emissions from naphtha gasoline PPC, ethanol PPC, methanol PPC and methanol diffusion combustion in terms of soot mass concentration, number concentration and particle size distribution in a single cylinder Scania D13 engine, while varying the intake O_2 . Intake temperature and injection pressure sweeps were also conducted. The fuels emitting the highest mass concentration of particles (Micro Soot Sensor) were gasoline and methanol followed by ethanol. The two alcohols tested emitted nucleation mode particles only, whereas gasoline emitted accumulation mode particles as well. Regarding soot mass concentration measurements; methanol never exceeded 1.6 mg/m^3 while when operating on gasoline this value never descended below 1.6 mg/m^3 . From this result it can be concluded that the main contributor to PM mass emissions is mainly increasing CMD (Count Mean Diameter) in the accumulation mode size range, but can in diffusion combustion also be caused by a high amount of nucleation mode particles. A probable cause of higher particle number emissions, when running the engine on methanol compared to ethanol, is the corrosiveness of the fuel itself. Except for the ultra-low PM mass emitted from alcohol combustion, it is also possible to alter the EGR concentration with a higher level of freedom without having to consider the NO_x - soot tradeoff.

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INTRODUCTION

Engineers in the transport automotive industry are working to meet the ever increasing exhaust emission demands while simultaneously competing for the highest possible fuel efficiency. While the CI (Compression Ignition) engine is generally accepted as the most fuel efficient engine in the automotive market, it has the drawbacks of emitting considerable amounts of soot and NO_x . Remedies, in form of EATS (Emission After Treatment System), to reduce these exhaust emissions exist, however, they are either complex in design, expensive or are in need of regular maintenance [1].

PM (Particulate Matter) emissions has recently attracted the attention of the legislative organs, and consequently, that of the engine manufacturers as well. PM has a wide range of negative effects on the environment, including health effects, ecological effects and visibility [2]. Apart from the environmental impact, it also contributes to

engine wear. Intake valve and combustion chamber deposits, PCV (Positive Crankcase Ventilation) and EGR (Exhaust Gas Recirculation) systems failures are all associated with PM [3].

It is possible to reduce the soot and NO_x emissions by utilizing the PPC strategy [4]. However, this strategy comes with a trade-off; increasing the EGR will increase the soot, while decreasing EGR will increase the NO_x emissions [5]. To avoid this trade-off completely, it is possible to use a fuel with a short carbon chain. Instead of using Diesel fuel (Swedish MK1) or the recommended naphtha gasoline (RON 70), it is possible to use alcohols, which are known to produce very little soot when combusted [6]. Another very important advantage of alcohols is the possibility to produce these fuels from biomass, further reducing the well-to-wheel CO_2 emissions [7].

The soot emissions in PPC operation depends, among other factors, heavily on the EGR utilization. Several studies have shown that all pipe soot emissions reach a local minimum when the inlet O_2

concentration is decreased to approximately 11-13% [8]. Reducing the intake O_2 concentration beyond this point will reduce the soot emissions due to a decreased soot formation rate resulting in a "soot bump" [9].

The typical diesel heavy duty PM particle consists mainly of carbon, unburnt oil, sulfate, water, ash and unburnt fuel, listed in descending order. It is worth mentioning that by number most solid particles, exhausted by Diesel and SI (Spark Ignition) engines operating in conventional conditions, are commonly attributed to the accumulation mode range of 50 - 100 nm in diameter, categorizing them as both nanoparticles and ultrafine particles [3][10]. However, also non-volatile particles in the nucleation mode range have been found in a few studies, and been linked to the metal content of lubrication oils [11].

It is known that a lower intake O_2 concentration, at a given intake pressure and fuel flow, will reduce λ , which will in turn increase the soot emissions. Shen et. al. [12] showed, that the FSN (Filtered Smoke Number) for diesel is approximately double that of gasoline for $\lambda \leq 1.3$. For Diesel PPC, FSN as high as ~ 9 was reported, which is way above 1000 mg/m³ in soot mass concentration [13]. In the same study, ethanol was utilized and consistently displayed FSN=0. It is therefore of interest to investigate the sooting behaviors of methanol and compare these with ethanol and gasoline.

The objective of this paper is to examine the behavior of the soot mass and solid particle number emissions of alcohol combustion, caused by extensive use of EGR. Experiments will be conducted for methanol and ethanol and compare those with naphtha gasoline, all running in PPC mode. Also, the EGR sweep will be conducted on methanol diffusion combustion. The comparison will include soot mass concentration, solid particle number concentration as well as size distribution. In addition to the effects of EGR, the soot generating effect of higher intake air temperature and injection pressure will also be examined. The HC, NO_x and CO trade-off during the intake O_2 concentration sweep will be studied for the three fuels.

METHOD

The objective of this paper, is to study emissions of methanol and ethanol and compare these with a naphtha gasoline. As alcohols have a very low tendency of emitting PM, the operation of the engine was primarily chosen to stimulate a heavy production of soot. Prior to the experiments, it was assumed that alcohols had a behavior similar to that of gasoline and diesel regarding PM emissions, although on a different concentration level.

Engine Setup

The experimental engine is a six cylinder Scania D13, which has been converted to operate only on one cylinder. Specifications of the engine is given in [Tab. 1](#) below.

Table 1. Engine specifications.

Displaced volume [cm ³]	2124
Stroke [mm]	160
Bore [mm]	130
Connecting rod length [mm]	255
Geometrical compression ratio [-]	15:1
Number of valves [-]	4
Swirl ratio [-]	2.1
Exhaust valve open [-]	137° ATDC
Inlet valve close [-]	-141° ATDC

Since the exhaust flow from a single cylinder is not adequate to run a turbo charger, pressurized air was supplied from an external in house compressor. The O_2 concentration in the inlet was regulated by a back pressure throttle and a EGR throttle. A 7.5 kW air heater was located between the fresh air supply and the intake manifold. The three exhaust sampling probes for the exhaust gas analyzers were located after the back pressure valve with the proper distance between them to avoid measurement inaccuracy due to flow disturbances. The test rig is displayed below in [Fig. 1](#).

The engine oil used in the engine is Statoil Powerway GE40. This lubricant is used mainly for gas engines. Unfortunately, the data sheet for the oil does not state any ingredients or amounts of minerals, which could play a significant role in PM formation.

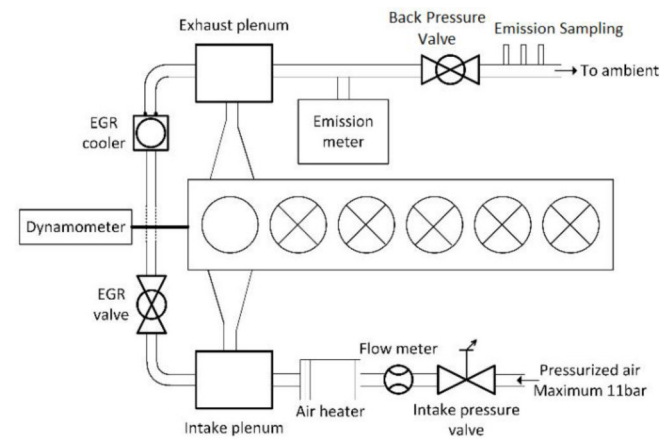


Figure 1. Schematic of the engine setup [14]

Emissions Systems

The exhaust gas constituents are measured in a AVL AMA i60 emission system. CO and CO₂ was measured using an IRD (Infrared detector), whereas NO_x and NO used a CLD (Chemiluminescence detector). It should be added that the CO₂ is measured both in the exhaust and intake, which grants the possibility to determine the EGR level. THC (Total Hydro Carbon) and CH₄ emissions was quantified

by an FID (Flame Ionization Detector). The NO_x and THC measurements were conducted wet, and the sample line was heated to approximately 192 °C to prevent the gases from condensing. Also it should be noted that CH_4 is included in the THC, and NO is included in the NO_x . Moreover, a PMD (Paramagnetic detector) was used to measure the concentration of O_2 in the exhaust, whereas O_2 in the inlet is calculated with equation (1), seen below.

$$O_{2,IN} = EGR(O_{2,EX} - O_{2,amb}) + O_{2,amb} \quad (1)$$

where $O_{2,EX}$ is the O_2 concentration in the exhaust and $O_{2,amb}$ is the ambient O_2 concentration set to a fix value of 20.95%.

Soot and Particle Measurement Systems

Two particle measurement devices were used in the campaign; AVL MSS (Micro Soot Sensor) and DMS500 (Cambustion Ltd, United Kingdom) Fast Engine Particulate Analyzer.

The AVL micro soot sensor measures soot particles using a photoacoustic technique. Soot is assumed to be black, being able to strongly absorbs modulated light ($\lambda = 808 \text{ nm}$), which is directed toward the flow path of the diluted exhaust gas. Particles will fluctuate in size, due to the heating and cooling, thus emitting a sound wave. This sound wave is detected by microphones and then translated into a concentration of soot. The MSS has a measurement range from 0.001 - 1000 mg/m^3 , and the sensitivity is in the level of $\mu\text{g/m}^3$.

In the DMS500, the particles are positively charged using a corona charger. The charge that the particles receives is approximately proportional to the surface area. The charged particles pass a strong radial electrical field and are deposited on different electrometer detectors depending on the electrical mobility of the particles. The currents from the 22 electrometers are measured and using an inversion matrix, the signal is transformed to a number particle size distribution with a maximum sampling rate of 10 Hz. This device measure particle size distribution ranging from $\sim 5 \text{ nm}$ to $1 \mu\text{m}$.

The exhaust aerosol was sampled using a heated sampling line at 150 °C with heated primary dilution of 5:1 at the sampling location to avoid condensation and agglomeration. After the sampling line, which is approximately 2 m long, the aerosol is diluted again and cooled down to room temperature using a high ratio secondary rotating disc diluter before measurement with the DMS 500. The second diluter can dilute up to 500 times, which makes the maximum dilution 2500:1. This sampling strategy is similar to that used in the EU PMP protocol, thus enabling sampling of solid particles only. This approach does not promote the formation of volatile nucleation mode particles as commonly occurs during tailpipe dilution to ambient air.

Experiments

All operation points conducted in this campaign had two conditions in common; speed and load at 1200 rpm and $\sim 6 \text{ bar}$ IMEP_G (Gross Mean Indicated Effective Pressure) respectively, except for the intake O_2 sweep conducted on methanol diffusion combustion where the load was set at

$\sim 10 \text{ bar}$ IMEP_G. The load was set at 21% O_2 in the intake, reducing the intake O_2 concentration will eventually affect the load negatively due to reduced combustion efficiency and slower combustion. Three fuels were used, and for each fuel, three sweeps were conducted. Properties of the three fuels can be seen in Tab. 2, below.

Table 2. Fuel specifications [15][16][17].

	EtOH	MeOH	Naphtha Gasoline
RON	108 - 109	107 - 109	69
MON	89	92	66
H/C	3	4	1.98
O/C	0.5	1	0
Q _{LHV} [MJ/kg]	26.7	19.9	43.68
(A/F) _s	9.00	6.47	14.68

It should be noted that none of the alcohol fuels used in this campaign where denatured. The ethanol and methanol used had the concentrations 99.5% and 99.85% respectively and the remaining part of the fuels is water and trace amounts of byproducts created during the distillation process. Also, 200 ppm Infineum R655 lubricant was used to prevent wear of the pumps and other mechanical parts. The chosen gasoline was Chevron naphtha gasoline with RON 69, as this is very close to the optimal fuel for PPC due to its ability to cover a very large load range [18].

Intake O_2 Concentration Sweep

The intake O_2 concentration sweep was conducted to induce the formation of soot emissions. Since it is known that the soot bump peaks at different O_2 concentration when altering the combustion phasing, CA50 was held constant at approximately 5 CAD (Crank Angle Degrees) BTDC (Before Top Dead Center). To counter a retarded combustion phasing when the O_2 concentration in the intake was reduced, the SOI was advanced. Also, during this sweep the injection duration was held constant, and as a result lambda, λ , was reduced with decreased intake O_2 concentration. The T_{IN} (Inlet temperature) was held constant at 175 °C for the ethanol and methanol sweep. Although a higher inlet temperature was required for methanol, this could not be achieved due to hardware limitations. T_{IN} for the naphtha gasoline intake O_2 concentration sweep was held constant at 140 °C. Also, the injection pressure during this sweep was kept constant at 1200 bar. Below, in Tab. 3, the operation matrix can be observed for the intake O_2 concentration sweep. In addition to the intake oxygen concentration sweep for the PPC cases, this sweep was conducted for methanol burning in conventional diffusion combustion mode.

The methanol diffusion combustion mode was conducted at similar conditions as written for methanol in the table above with one major difference; the IMEP_G was set to 10 bar at 21%. Since the load was higher, it was possible to reach an intake O_2 concentration of 11%. As the EGR is increased, the SOI was advanced to maintain CA50 at $\sim 5 \text{ CAD}$ BTDC. It was not possible to run diffusion combustion on this setup with a single injection, a double injection strategy had to be utilized. The first injection was set to 12 CAD BTDC and the main injection at 4 CAD BTDC, with no specific requirement on the pilot injection. The injected mass for the first injection was 21% and the

rest was injected by the main injection [19]. Below, in Fig. 2, it is possible to see the SOI as a function of the intake O_2 concentration, T_{IN} and common rail pressure.

Table 3. Operation matrix for intake O_2 concentration sweep.

Fuel	MeOH	MeOH Diffusion	EtOH	Naphtha Gasoline
Intake temperature [°C]	175	175	175	140
Load IMEP _G [bar] @ 21 % intake O ₂ conc.	~6	~10	~6	~6
Injection pressure [bar]	1200	1200	1200	1200
Intake O ₂ concentration [%]	21 - 14	21 - 11	21 - 10	19 - 10

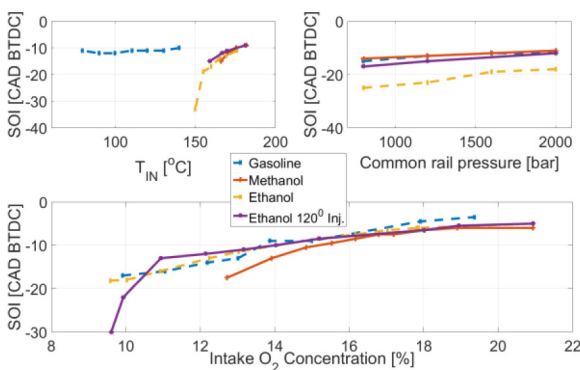


Figure 2. SOI vs T_{IN} , common rail pressure and intake O_2 concentration.

Intake Temperature Sweep

It is known that a higher combustion temperatures result in higher soot formation [20]. In this part of the experiments, the T_{IN} where swept. Since a decreased T_{IN} also results in an extended ignition delay and slower combustion, it was necessary to advance the SOI in order to maintain the combustion phasing constant; CA50 at ~5 CAD ATDC (After Top Dead Center). Below, in Tab. 4, the operation matrix for the T_{IN} sweep can be observed.

Table 4. Operation matrix for intake temperature sweep.

Fuel	MeOH	EtOH	Naphtha Gasoline
Intake temperature [°C]	182 - 166	180 - 150	140 - 80
Load IMEP _G [bar] @ 21 % intake O ₂ conc.	~6	~6	~6
Injection pressure [bar]	1200	1200	1200
Intake O ₂ concentration [%]	15	13	13

It is of importance to mention that the T_{IN} sweep was conducted at a lower intake O_2 concentration than ambient in an attempt to stimulate PM emissions from the alcohols. The intake temperature sweep was

conducted at a higher intake O_2 concentration than for ethanol and naphtha gasoline due to combustion difficulties caused by a substantially high charge cooling effect. Although a higher intake O_2 concentration was utilized, it was not possible to have a big interval between the highest and lowest T_{IN} .

Injection Pressure Sweep

Injection pressure is ideally kept as low as possible to avoid high losses categorized within the friction losses. However, decreasing the injection pressure will increase the soot formation, when utilizing fuels with a tendency to emit soot. In this study, the injection pressure was varied from 800 bar to 2000 bar in increments of 400 bar. To keep the load constant, the injection duration was increased for lower rail pressures and vice versa. Also, to keep the CA50 constant at ~5 CAD ATDC, the SOI had to be advanced when decreasing the rail pressure. In Tab. 5 the operation conditions for this sweep can be observed.

Table 5. Operation matrix for injection pressure sweep.

Fuel	MeOH	EtOH	Naphtha Gasoline
Intake temperature [°C] @ 21 % intake O ₂ conc.	175	175	50
Load IMEP _G [bar]	~6	~6	~6
Injection pressure [bar]	800 - 2000	800 - 2000	800 - 2000
Intake O ₂ concentration [%]	14	14	14

As it can be noticed, the injection pressure sweep was conducted at a lower temperature for naphtha gasoline to avoid extremely sooty operation points. Also, a low temperature helps keeping the maximum pressure rise rate low to avoid a too violent combustion. The intake O_2 concentration was held constant at 14% so it would be possible to compare with methanol.

Fuel Injectors

Injector 1 is basically a stock Scania Euro V injector with one major difference; the umbrella angle is narrower. Since PPC operation generally requires an advanced SOI in comparison to CDC (Conventional Diesel Combustion), the umbrella angle is made narrower to be able to aim the fuel completely inside the piston bowl. The umbrella angle for this injector is 120°, in comparison to the stock umbrella angle which is 148°.

Injector 2 is a Scania Euro VI injector with internal materials changed (mainly the polymer material that the gaskets are made of) to be able to handle the corrosivity of alcohols, especially that of methanol. Due to the low stoichiometric air fuel ratio of methanol, this injector has a higher number of orifices to be able to inject with an increased fuel flow while keeping the injection duration short. Observed below is a table containing some specifications for both injectors used. It is worth mentioning that the high pressure pump was somewhat modified to handle ethanol and during the experiments no problems related to the corrosivity of alcohols were encountered.