

Fuel-Independent Particulate Emissions in an SIDI Engine

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ABSTRACT

The fuel-independent particulate emissions of a direct injection gasoline engine were investigated. This was done by running the engine with reference gasoline at four different loads and then switching to hydrogen or methane port fuel operation and comparing the resulting particulate emissions and their size distribution. Differences in the combustion characteristics of hydrogen and gasoline were accounted for by diluting the inlet air with nitrogen and matching the pressure or heat release traces to those of gasoline operation.

Methane operation is expected to generate particulate emissions lower by several orders of magnitude compared to gasoline and hydrogen does not contribute to carbon soot formation because of the lack of carbon atoms in the molecule. Thus, any remaining particulate emissions at hydrogen gas operation must arise from non fuel related sources, e.g. from lubrication oil, metal abrasion or inlet air. With methane and hydrogen operation, only a very small amount of particles larger than 30 nm could be measured. The comparison between CEC reference fuel and hydrogen operation showed similar size distributions for particles smaller than 10 nm at low loads, which was also consistent with the comparison between methane and gasoline operation.

The tentative conclusion is that particles smaller than 10 nm do not, for the most part, originate from the combustion of the fuel. However, at higher loads, the differences between gasoline and hydrogen operation were more pronounced at all particle sizes. Thus, while there seems to be a fuel-independent baseline of particulate emissions, the contribution of the fuel combustion itself is also important and is the dominant contribution at higher engine loads.

CITATION: Maier, A., Klaus, U., Dreizler, A., and Rottengruber, H., "Fuel-Independent Particulate Emissions in an SIDI Engine," *SAE Int. J. Engines* 8(3):2015, doi:10.4271/2015-01-1081.

INTRODUCTION

The worldwide demand for mobility has led to many innovations that allow comfortable transportation and simultaneously the reduction of fuel consumption and pollutant emissions. The introduction of gasoline direct injection (GDI) has contributed to these trends. However, reducing the particulate emissions of gasoline engines has recently become a topic of interest, especially due to the introduction of limits for particulate emission in GDI engines with the Euro 6b emission standard of 2014. The limits of $6 \cdot 10^{12}$ particulates per kilometer in 2014 will be tightened to $6 \cdot 10^{11}$ particulates per kilometer with the introduction of the EU6c legislation in September 2017.

Due to the in-cylinder mixture preparation and limited time of air-fuel mixing, gasoline fuel direct injection tends to be very sensitive to changes in the application of the engine. The main

sources of particulate formation during combustion are the wetting of surfaces such as the intake valves, cylinder liner and piston and poor mixture formation leading to combustion in fuel rich areas. However, the overall particulate emissions are often a combination from different particulate sources that could also have confounding roots.

In this work, the contribution of the fuel is investigated in order to isolate it from and to identify the significance of the non-fuel related particulate emissions. For example, Jung et al. [1] added lubricating oil to the Diesel fuel and observed an increase in particulate numbers by an order of magnitude. Other researches tried to identify the non-combustion chemistry based influence of the fuel on particulate formation. Hageman et al. [2] completely pre-vaporized the air-fuel mixture to eliminate fuel-rich pockets inside the cylinder. By varying the equivalence ratio they could identify a reproducible particulate baseline that was not related to the carbon content of the fuel.

et al. [3] have reconfigured a four cylinder heavy duty Diesel off-road engine to spark ignited hydrogen ignition. The tailpipe particulate emissions at three different loads showed a significant amount of particles even though the hydrogen combustion cannot be an origin of particulates. These results from a reconfigured Diesel engine were the motivation to perform the investigations described in this report. A light duty single cylinder engine was used and the particulates were sampled in the exhaust manifold.

EXPERIMENTAL SETUP

Engine Setup

The engine used for this experiment was a single-cylinder direct injection spark ignited Ricardo Hydra engine modified in order to allow for gasoline as well as hydrogen or methane operation. The fuel injector from a current production series was located in the center of the cylinder head. The spark plug was mounted between the two exhaust valves. Relevant dimensions of the engine can be found in [Table 1](#). European emission certificate fuel (CEC RF-02-03) containing no ethanol was chosen as the gasoline reference (CEC). CEC was injected with a six-hole injector with a start of injection timing of 300 °BTDC. The spray pattern of the multihole-injector was reasonably chosen, but not specially optimized towards particulate emissions of this engine geometry. The spark timing was adjusted such that the location of 50 % cumulative heat release (CA50) point was at 8 °ATDC. The gas injection into the intake manifold was performed continuously with Bronkhorst mass flow controllers. It is expected that the gaseous fuels are well mixed with air in the cylinder at the time of ignition. Compared to the gasoline direct injection, there should be less locally rich fuel zones in the cylinder that are believed to be an important particulate formation source. Flame arresters were installed such that the premixed air-hydrogen mixture was limited to 250 ml in the intake manifold. Valve overlap was also reduced to minimize the risk of backfire into the intake manifold during gas operation. The intake air was assured to be dry and particle free. The engine was lubricated during the tests with synthetic 5W30 oil.

Table 1. Engine geometry specification

Displaced volume	500 cm ³
Stroke	86 mm
Bore	82 mm
Compression ratio	10.5:1
Number of Valves	4
Exhaust Valve Open	118° ATDC @ 0.1 mm lift
Exhaust Valve Close	362° ATDC @ 0.1 mm lift
Inlet Valve Open	361° ATDC @ 0.1 mm lift

Particle Measurement Setup

The particulate measurement setup ([Figure 1](#)) consists of a Dekati FPS-4000 dilution tunnel with an evaporation chamber and an additional diluter DI-1000 and either a TSI Scanning Mobility Sizer (SMPS) or a TSI Engine Exhaust Particle Sizer (EEPS). The SMPS consists of a DMA 3085 and CPC 3776 that allow the measurement

of particle sizes from 2 nm to 60 nm. The EEPS system measures particle sizes from 5.6 to 560 nm and was used to gain insights of the particulate size distribution (PSD) above 60 nm. The FPS 4000 dilution ratio was at small levels of 25:1 as particle numbers were close to the lower particulate count limit of the condensation particle counter (CPC). The primary dilution air of the FPS 4000 was heated up to 350 °C. A volatile particle remover (VPR) was implemented upstream of the SMPS 3936. The VPR consisted of an evaporation chamber heated to 400 °C and a Dekati DI-1000 ejector diluter with dilution ratio of about 11:1 leading to a total dilution ratio of about 275:1.

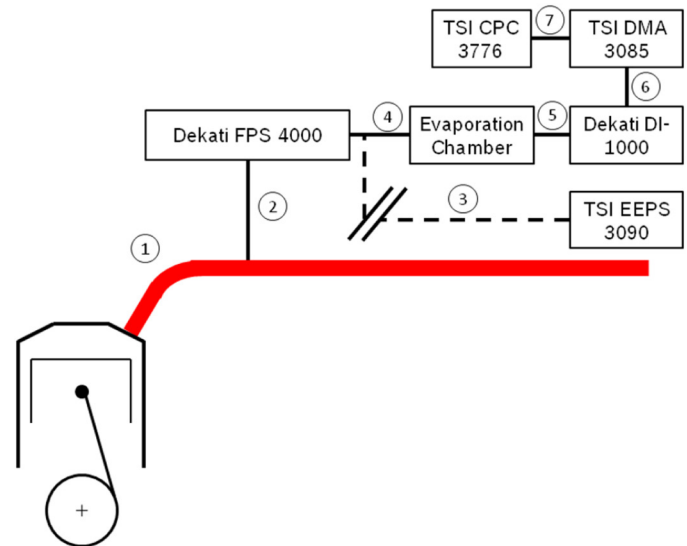


Figure 1. Particle measurement setup, dimensions in [Table 2](#).

The diffusion loss correction of the SMPS was activated but no correction for the losses in the sampling tube was applied. The diffusion losses have been determined experimentally or have been calculated for all different flow paths in the SMPS. The diffusion loss correction can be very strong, e.g. the number count of a 10 nm particle gets corrected for by 230 %. Further details can be found in [\[4\]](#) and [\[5\]](#). The lengths of the parts in the particle sampling line are listed in [Table 2](#). The total length from exhaust valve to SMPS inlet was about 1.76 m. The sample probe was installed 140 mm downstream of the exhaust valve and the tip was located 30 mm inside the exhaust manifold.

Table 2. Lengths in the particle measurement setup ([Figure 1](#))

Part	Length (mm)	Part	Length (mm)
Dekati FPS 4000	500	4	290
Evaporation chamber	230	5	70
1	140	6	310
2	220	7	330
3	620		

Hydrogen Test Procedure

[Table 3](#) shows the properties of the three different fuels which were used in this work.

Table 3. Properties of hydrogen compared to gasoline and methane

Property	Unit	Gasoline	H ₂	CH ₄
Stoich. air-fuel mix. [6]	kg _{air} /kg _{fuel}	14.53	34.3	17.2
Lower heating value [6]	MJ/kg	43.15	120	50
Heating value of stoich. Air-fuel mix [6]	MJ/m ³	3.82	3.2	3.4
Ignition limit in air [6]	Vol%	1...7.6	4...76	5.3...15
Minimum ign. Energy [6]	mJ	0.24	0.02	0.29
Lam. flame velocity stoich. Air-fuel mix[6]	cm/s	40-80	200	40
Quenching distance at 300 K and 1 atm [7]	mm	3.5 (C ₈ H ₁₈)	0.64	2.03
Mass fraction C	%	86.75	0	74.9
Mass fraction H	%	13.25	100	25.1
Mass fraction O	%	<0.01	0	0

Hydrogen differs highly from the combustion characteristics of CEC fuel. At hydrogen operation, the much faster heat release due to the higher laminar flame speed compared to gasoline has to be accounted for. Additionally, hydrogen is prone to pre-ignition due to the low minimum ignition energy, shorter quenching distance and wider flammability range.

Both effects can be diminished by diluting the air-fuel mixture with nitrogen to increase the specific heat capacity of the mixture. Nitrogen was chosen in order to keep the equivalence ratio at 1 as nitrogen does not alter the oxygen balance in the combustion. A possible influence in the nitric oxide (NO_x) formation was accepted. Due to the lower volumetric energy density of gaseous hydrogen compared to liquid gasoline and the additional dilution with nitrogen, the manifold pressure had to be increased under hydrogen operation. In addition, the flame arrestors throttled the air flow and thus had to be compensated for by higher intake pressures. With variations of the amount of diluting nitrogen and changes in the spark timing only, it was not possible to adjust the heat release and the pressure curves of the hydrogen operating conditions to the reference gasoline baselines simultaneously. As the contribution of engine oil to the particulate emissions might vary for different strategies of matching gasoline to hydrogen operation, it was decided to investigate two different hydrogen operation strategies. In the first case, the in-cylinder pressure was adjusted (Figure 2) leading to different heat release curves. Criteria for the adjustment were the peak cylinder pressure as well as the pressure at 8 °ATDC. The adjustment of the pressure led to an integrated heat release of about 560 kJ/m³ for the hydrogen operation compared to about 750 kJ/m³ for the CEC operation. The pressure adaption creates similar contact pressure in the compression or oil rings and is expected to lead to similar residuals in the crevice volumes.

The second case was adjusted to match heat release rates (Figure 3) leading to much higher peak pressure signals compared to the gasoline reference. The latter case imitates similar vaporization effects of the engine oil on the liner. The heat release rate calculation was done online with the AVL 671 Indimaster system. The adaption

of the heat release rate results in much higher peak cylinder pressures, resulting in higher contact pressure between the compression or oil rings and the cylinder liner.

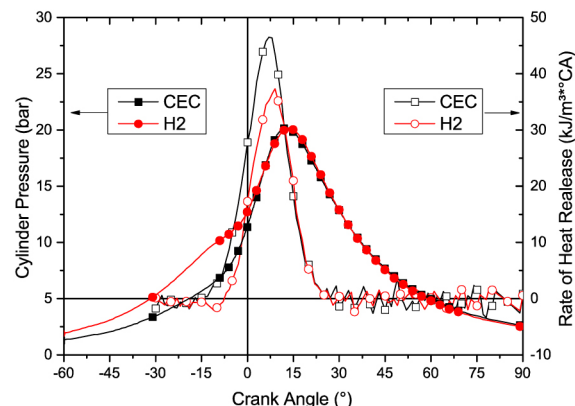


Figure 2. Cylinder pressure (closed symbol) and heat release rate (open symbol) for a 3 (bar) IMEP running condition with matched cylinder pressure for CEC and hydrogen fuel

Four different engine load conditions at 2000 RPM engine speed were investigated. The chosen engine load conditions of 2, 3, 6 and 8 bar IMEP are part load conditions. These load levels are representative for a New European Driving Cycle (NEDC) for a four cylinder engine with comparable engine geometry to this single cylinder engine. Table 2 shows the corresponding gas flows used to adjust the load of the CEC reference gasoline.

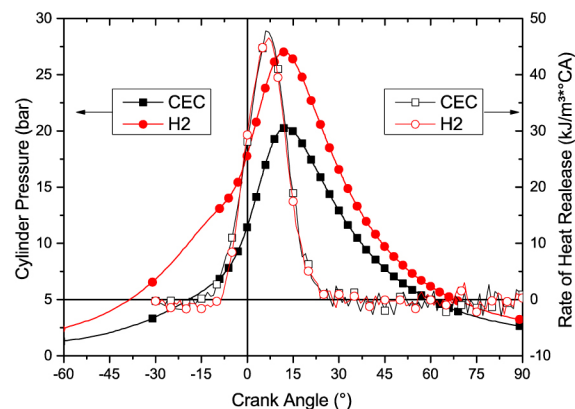


Figure 3. Cylinder pressure (closed symbol) and heat release rate (open symbol) for a 3 (bar) IMEP running condition with matched heat release for CEC and hydrogen fuel

Table 2. Gas flows for adjustment of in-cylinder pressure or heat release curve to CEC reference gasoline

Load in bar IMEP @ 2000 RPM	Adaption	Air in slpm	Additional N ₂ in slpm
2	p _{Cyl}	63	55
	d _{Qh}	81	90
3	p _{Cyl}	83	70
	d _{Qh}	110	99
6	p _{Cyl}	145	125
	d _{Qh}	183	135
8	p _{Cyl}	190	163
	d _{Qh}	249	163