

Particulate Matter Emissions from a Direct Injection Spark Ignition Engine under Cold Fast Idle Conditions for Ethanol-Gasoline Blends

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ABSTRACT

The engine out particulate matter number (PN) distributions at engine coolant temperature (ECT) of 0° C to 40° C for ethanol/ gasoline blends (E0 to E85) have been measured for a direct-injection spark ignition engine under cold fast idle condition. For E10 to E85, PN increases modestly when the ECT is lowered. The distributions, however, are insensitive to the ethanol content of the fuel. The PN for E0 is substantially higher than the gasoline fuels at ECT below 20° C. The total PN values (obtained from integrating the PN distribution from 15 to 350 nm) are approximately the same for all fuels (E0 to E85) when ECT is above 20° C. When ECT is decreased below 20° C, the total PN values for E10 to E85 increase modestly, and they are insensitive to the ethanol content. For E0, however, the total PN increases substantially. This sharp change in PN from E0 to E10 is confirmed by running the tests with E2.5 and E5. The midpoint of the transition occurs at approximately E5. Because the fuel evaporative property does not change substantially from E0 to E10, the significant change in PN is attributed to the particulate matter formation chemistry.

INTRODUCTION

The potential for improved fuel efficiency and reduced greenhouse gas emissions renders the turbo-charged Direct Injection Spark Ignition (DISI) engine an attractive choice for light-duty applications. The key positive attributes of the DISI engine are the charge cooling effect (better volumetric efficiency; improved knocking limit; higher compression ratio), and the precise fuel metering into the cylinder (reduction of over fueling in cold-start; better mixture preparation; improved transient response). There are, however, drawbacks. DISI engines emit higher Hydrocarbon

(HC) and Particulate Matter (PM) than traditional Port Fuel Injection (PFI) gasoline engines, especially during the cold-start and warm up period [1]. Measured PM emissions in vehicles equipped with DISI engines in standard driving cycles exceed the regulated values for diesel engines in Europe (EU5, EU6), both in terms of mass and concentration [2]. Although Particulate Matter Number (PN) from gasoline engines have not been legislated yet in USA nor in Europe, several healthy studies have related PM to both environmental pollution and human health risks such as respiratory diseases, heart-attacks, and cancer. The health effects are found to correlate more with the size of PM and less with the mass [3].

Gasohols, mostly 10% Ethanol-90% Gasoline blend (E10), have been introduced as fuel for passenger cars in the USA since 1980's. Pure ethanol (E100) is used in warm climate areas such as in Brazil. Increased use of ethanol (e.g. E25, E85) has been proposed as a means to reduce oil import dependency. Other benefits are combustion improvement and reduction of toxic and carcinogenic compounds in the fuel. Higher oxygenated contents in fuels have been observed to reduce PM emission in diesel engines [4, 5]; the impact of fuel oxygenates on DISI engines needs to be accessed. Previous studies have investigated the DISI PM emissions (PM composition, mass, and number) in cold-start using gasoline [6, 7], and the impact of fuel ethanol content on PM emissions at part or high load [1, 8, 9].

The work presented here investigates the effects of ethanol percentage in ethanol-gasoline blends (E0 up to E85) on PM emissions from a homogeneous charge DISI engine during the cold-fast-idle period. Both the PN distribution and total PN emitted (in the 15-350 nm range) are studied. The focus is on the emissions directly from the cylinder; the exhaust

sampling point is 15 cm downstream of the exhaust valves. The PN distributions have been taken using a TSI Scanning Mobility Particle Sizer System (SMPS). The results presented here are for a coolant temperature range between 0° and 40°C. The engine load, speed, injection time, spark time, and λ are representative for the cold-fast-idle period.

EXPERIMENTAL SETUP AND PROCEDURES

A sampling system has been designed to transfer and condition the exhaust gas 15 cm downstream of the exhaust valve to a TSI Scanning Mobility Particle Sizer (SMPS). The instrument measures the electric mobility equivalent diameter of the PM and presents the results as a PN distribution. The following sections describe the experimental apparatus, starting from the engine specifications and running conditions, and then present the sampling system and the process used to validate it.

ENGINE DESCRIPTION

The experiments have been conducted on a GM Ecotec 2.2 L, naturally aspirated, DISI, 4-cylinder engine, which has been modified for single cylinder operation ([table 1](#)).

Table 1. Engine Specification.

Displaced volume per cylinder	550 cc
Stroke	94.6 mm
Bore	86 mm
Compression ratio	12:1
Number of Valves	4
Exhaust Valve Open	44.5° BBDC
Exhaust Valve Close	10.5° ATDC
Inlet Valve Open	0° ATDC
Inlet Valve Close	60° ABDC
Injector Center Line	47° from horizontal
Nominal Cone Angle (figure 2)	52°

The engine is equipped with a charge motion control valve at the intake port to provide a swirling charge motion at part load ([Fig. 1](#)). The intent of this work is to investigate low load operation, so the valve is closed (swirl-enabled).

The engine coolant temperature (ECT) is controlled by a commercial chiller and heater combination. The experimental results presented here have been taken under a variety of temperatures: 0°C, 7°C, 15°C, 20°C, 30°C and 40°C. For experiments at ECT lower than atmospheric, the coolant is also used to control the fuel temperature through a heat exchanger. To control the fuel pressure the engine fuel pump has not been used. Instead, the premixed ethanol/gasoline blends are supplied from individual accumulators pressurized by high pressure nitrogen. The fuel lines are arranged so that

in fuel switching, residual fuel is removed by a vacuum pump and then the fuel line is flushed with the new fuel. The flushing process is validated by observing the change in fuel pulse width under stoichiometric condition when the fuel is switched from gasoline to E85.

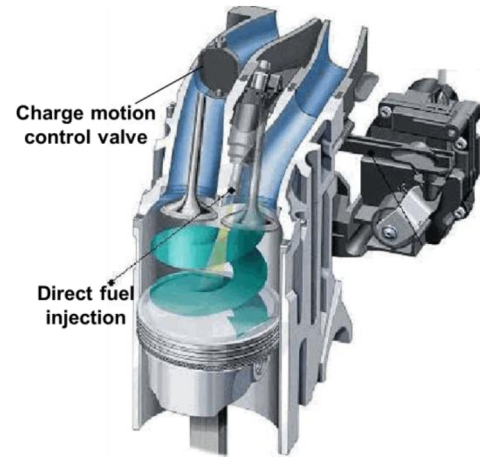


Fig. 1. Charge motion control valve and injector arrangement. Under low load the charge motion control valve is close, providing a swirl motion to the intake air.

The fuel spray has a nominal cone angle of 52°, with the center line at 47° from the horizontal ([Fig. 2](#)). The actual spray geometry will depend on the injection and cylinder pressure.

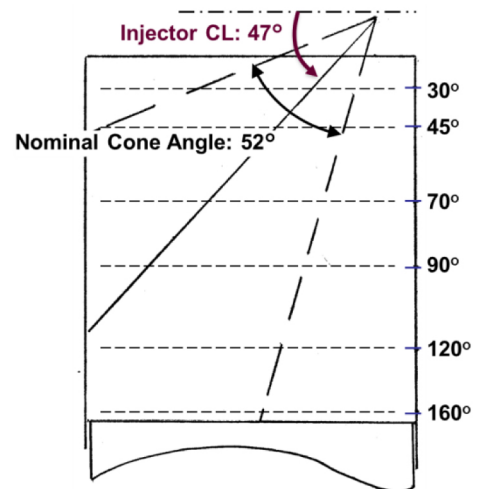


Fig.2. Nominal Spray Geometry. The horizontal dotted lines mark the piston positions at the labeled values of crank angle after TDC.

The amount of fuel injected into the cylinder is controlled by a feedback system to maintain the desired λ value, as measured by the exhaust λ sensor. A certification gasoline (Haltermann HF437: 97 RON; 89 MON and RVP 1.36 bar) is used as the base fuel. Anhydrous ethanol is mixed to the base

fuel by volume to create the experimental fuel matrix (table 2). It should be noted that in commercial E10, the gasoline base fuel is different from the nominal gasoline so as to improve the vaporization characteristics and to maintain the octane number.

Table 2. Experimental Matrix: Each fuel has been tested under the same engine's operational condition, simulating cold-start, for a variety of coolant temperature range (between 0°C and 40°C).

	Gasoline Portion (% by vol.)	Gasoline Portion (% by vol.)
E0	100%	0%
E2.5	97.5%	2.5%
E5	95%	5%
E10	90%	10%
E25	75%	25%
E50	50%	50%
E85	15%	85%

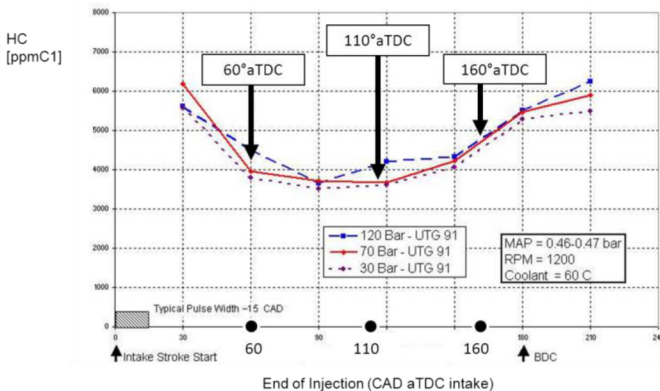


Figure 3. HC emissions as a function of End-Of-Injection (EOI) time (as CA aTDC-intake); fuel pressure at 30, 70 and 120 bar [8].

In order to isolate the effect of different fuels, the engine speed, MAP, fuel pressure, spark timing, injection timing, and λ have been kept constant for all experiments. For this engine, nominal injection is during the intake period to produce a homogeneous charge. The HC emissions are relatively constant for EOI timings between 60 and 150°CA ATDC-intake, and for a range of fuel pressures between 30 to 120 bar (see Fig. 3). A fuel pressure of 70 bar has been chosen. The EOI timing has a significant effect on PM formation. Fig. 4 shows the PN distribution for three different EOI timings under steady state running condition. For EOI close to 110°CA ATDC-intake the engine emits much less PM than for 50°CA before or after. The observation is mainly due to fuel-piston impingement effects (early EOI) and to bad mixing effect (late EOI). A value of EOI of 120°CA ATDC-intake is used. The ignition time is fixed at 15°CA BTDC,

which is retarded from the MBT timing for all fuels; this practice is consistent with typical cold-idle strategy.

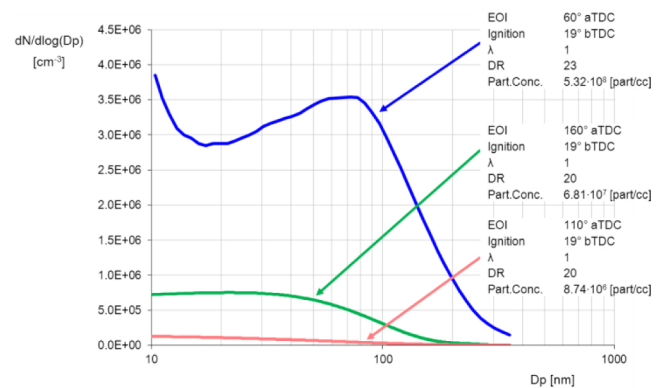


Figure 4. PN distributions for EOI at 110° ATDC (intake) are an order of magnitude lower than 50° later or earlier. Engine at steady state: nimep = 3.8 bar, speed = 1,500 rpm, fuel: EO, fuel pressure = 70 bar, stoichiometric combustion ($\lambda=1$).

SAMPLING SYSTEM AND INSTRUMENTATION

The particulate matter number (PN) distribution is measured with a TSI Scanning Mobility Particle Sizer (SMPS) system (Differential Mobility Analyzer (DMA), model 3071A coupled with a Condensation Particle Counter (CPC), model 3010). The input gas passes through an impactor to remove particles larger than 10 μm , and then through a bipolar charger. The charged particles and a particle-free stream of air are separately introduced into one end of a tubular chamber with a centrally mounted electrode in the DMA. Particles with higher or lower mobility are respectively deposited on the electrode and carried out in the excess flow. Particles within a preselected size range passes through Butanol vapor, where they evenly grow in size (so they can be detectable) and then they are counted optically in the CPC. The electric field in the DMA is scanned to produce a PN distribution curve as a function of the equivalent mobility diameter (D_p).

To stay within the dynamic range of the instrument, a dilution tunnel has to be designed to reduce the temperature and the PM number concentration of the exhaust gas sample before it enters in the SMPS. During the dilution process any PM losses (diffusion, thermophoresis, nucleation and coagulation) have to be minimized. For this purpose a one stage mini-dilution tunnel has been constructed that uses N_2 as the diluent. The exhaust gas sampling point is 15 cm after the exhaust valves. The temperature of the exhaust gas at that point is approximately 420°C. In order to avoid PM losses, the sampling tube length is kept short: mixing with N_2 takes placed 15 cm from the sampling point (Fig. 5). To avoid