

Assessment of Gasoline Direct Injection Engine Cold Start Particulate Emission Sources

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ABSTRACT

The gasoline direct injection (GDI) engine particulate emission sources are assessed under cold start conditions: the fast idle and speed/load combinations representative of the 1st acceleration in the US FTP. The focus is on the accumulation mode particle number (PN) emission. The sources are non-fuel, combustion of the premixed charge, and liquid fuel film. The non-fuel emissions are measured by operating the engine with premixed methane/air or hydrogen/air. Then the PN level is substantially lower than what is obtained with normal GDI operation; thus non-fuel contribution to PN is small. When operating with stoichiometric premixed gasoline/air, the PN level is comparable to the non-fuel level; thus premixed-stoichiometric mixture combustion does not significantly generate particulates. For fuel rich premixed gasoline/air, PN increases dramatically when lambda is less than 0.7 to 0.8. This lambda threshold does not correlate with engine speed and load; however, it increases slightly when the intake air is diluted with nitrogen. To assess the fraction of the GDI injected fuel that contributes to the PN, at fixed load and lambda, the injected gasoline is systematically reduced, with premixed methane as balance for the fuel. It is found that only a small fraction of the injected fuel contributes to the PM emissions. The fraction is dependent on the fuel amount and the rigor of the mixing process; hence it is dependent on speed, load, and timing of the injection.

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INTRODUCTION

The gasoline direct injection (GDI) technology [1] is an important enabler for boosted downsize spark ignition engines which are employed to meet the increasingly stringent fuel economy requirements [2]. The in-cylinder injection cools the charge, thereby increases the engine knock resistance and volumetric efficiency [3, 4]. The GDI engines, however, have much higher particulate matter (PM) emission than the port-fuel-injection (PFI) engines, especially during cold start [5, 6, 7, 8], because of the substantial presence of incylinder liquid fuel film due to the direct injection. (In PFI engines under part load condition, there is a reverse flow from the cylinder to the intake manifold when the intake valve opens [9]. This flow substantially spreads the port liquid fuel over the port and manifold surfaces, thereby facilitates evaporation and reduces the amount of liquid fuel transport into the cylinder.) PM emission in GDI engines is a major concern.

The fine particle emissions are particularly important because of their impact on health effects [10, 11, 12]. Regulations have been established to constrain the particle number (PN). The Euro VI regulation calls for a limit of 6×10^{11} particles/km for light-duty vehicles [13]. The PN is measured according to the particle measurement protocol (PMP) [14]. The number comprises the solid

(non-volatile) particles in the 23 - 2500 nm range. These are particles mostly in the accumulation mode of the particle size spectrum [15].

Spark-ignition engine particulate emission sources comprise of:

- Non-fuel sources - from the lubrication oil, combustion chamber deposit, ...
- Particles formed from the locally fuel rich regions of the premixed flame.
- Particles from pyrolysis in the fuel rich region of the vapor plume derived from the wall liquid fuel films [16].

The objective of this work is to assess the contributions of these sources under engine cold start condition by a series of experiments that isolates the different sources.

METHODOLOGY

Engine

Measurements are made in a modern boosted GDI spark-ignition engine (the GM - LTG engine which powers various models of the Cadillac and Malibu vehicles). The engine specifications are shown in Table 1.

Table 1. Specification for the LTF engine.

Displaced volume	1998 cc
Stroke	86 mm
Bore	86 mm
Connecting Rod	145 mm
Compression ratio	9.2:1
Exhaust Valve Open (parked cam)	52° BBDC @ 0.2 mm lift
Exhaust Valve Close (parked cam)	10° BTDC @ 0.2 mm lift
Inlet Valve Open (parked cam)	11° ATDC @ 0.2 mm lift
Inlet Valve Close (parked cam)	61° BBDC @ 0.2 mm lift

The engine is reconfigured to run as a single cylinder engine on cylinder #1, which is equipped with its own intake and exhaust runners. Intake air is supplied by a motor driven screw compressor capable of boosting to a MAP of 1.7 bar. The overall schematic of the engine is shown in Fig. 1.

The engine is controlled by a computer by which the spark timing, injection timing, and injection duration could be specified. The cam phasers for the valve timing control are not energized so that the cam phasers are at the parked positions.

All the results have been obtained at steady state engine condition as indicated by that the measurements are no longer changing with time. It takes nominally 1 minute to achieve steady state condition for GDI operations, and, because of the low emission level (close to ambient value), up to 10 minutes for the premixed charge operations.

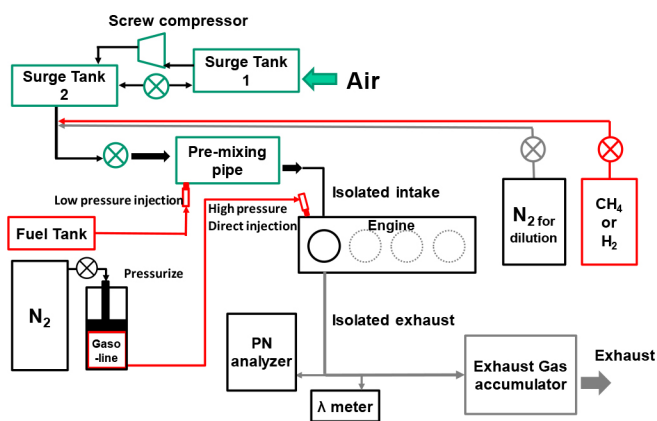


Figure 1. Schematic of engine, fuel supply, and measurement system.

Fuel Delivery System

It will be discussed in the subsequent sections that besides the direct injection of the original engine, several fuel supplies are used in the experiment. The supplies include pre-vaporized-premixed gasoline, methane, and hydrogen. The latter two fuels are used to assess the engine non-fuel PM emissions. The gasoline used in the experiments is a certification gasoline (Haltermann HF437, with 97.4 RON, 89 MON and RVP of 62 kPa). A schematic of the overall system is shown in Fig. 1.

Gasoline Direct Injection

The engine uses a wall-guided direct injection strategy with a side-mounted injector inclined at 25° from the horizontal. The injector has 6 holes with a spray cone angle of 52°. The fuel for the direct injection is supplied by a fuel bladder pressurized with bottle nitrogen gas. The fuel pressure can be regulated from 30 to 150 bar. The nominal injection pressure is at 50 bar.

Pre-Vaporized-Premixed Gasoline

Pre-vaporized-premixed gasoline mixture is used to assess the PM production in the engine nominal premixed flame. This fuel is prepared via a port-fuel-injector (operating at 3.5 bar injection pressure) that sprays the gasoline onto the heated surface (at 80° C) of a tube in which the intake air passes through. To ensure adequate mixing, the mixture passes through a long mixing pipe before entering the intake manifold of the engine.

Gaseous Fuel Supply

The gaseous fuels (methane and hydrogen) are introduced far upstream in the intake system to ensure good mixing between the gases and the intake air.

PN Measurement

The particles are measured by the Cambustion DMS 500 Fast Particle Sizer equipped with a rotating disk type dilutor [17]. The instrument measures the distribution of the exhaust gas particles effective mobility diameter. (The term effective is used because the measured mobility diameter results from the combined effects of the true mobility diameter and the efficiency of attaching a charge to the particle. The charge attachment is dependent on the shape and size of the particle; see application notes in Ref. [17].) The sample is taken from the exhaust runner at approximately 15 cm from the exhaust valve, and with the sampling line heated to 150° C; the procedure is consistent with the PMP.

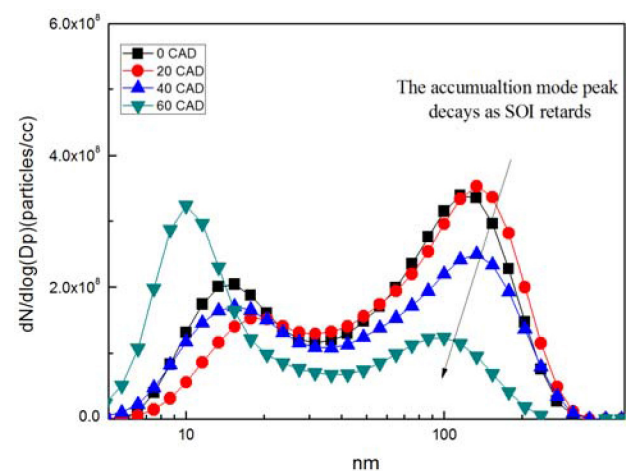


Figure 2. Typical particle size spectra. The spectra are for different SOI (as CAD ATDC-intake); engine at 1200 rpm, 2 bar NIMEP.

The software of DMS500 uses log-normal distributions to separate the nucleation and the accumulation modes of the distribution. Typical particle size spectra are shown in Fig. 2, from which the distributions for the nucleation and the accumulation can be identified and fitted accordingly.

The total particle number N (as number of particles per standard cubic centimeter (#/cc)) is obtained by integrating the respective part of the PM spectrum associated with the accumulation and nucleation modes:

$$N_{\text{accum. or nucl.}} = \int \left[\frac{dN}{d \log(D_p)} \right]_{\text{accum. or nucl.}} d \log(D_p) \quad (1)$$

The size bin range of the instrument is from 5 to 1000 nm. However, there are not many particles above 1000 nm, and that the number of nucleation mode particles above 23 nm is relatively small (compared to the total number accumulation mode particles). Thus N_{accum} is a good measure of the total number of 23-2500 nm particles called out in PMP.

The DMS500 has a data rate (for scanning all the size channels) of 10Hz. The data reported are averaged over a period of 10 seconds. Each data point comprises at least 3 measurements to establish consistency.

Operating Points of Interest

Since cold-start PN is of interest, the water and lubricant temperatures are kept at 25° C. λ is kept at stoichiometric except for experiments with λ sweeps. Spark timing is adjusted for CA50 = 7° aTDC so that combustion phasing is approximately at optimum. The COV of the NIMEP is kept under 10% (some results have been rejected in the SOI sweep experiments because of the high COV). Note that the optimum spark timing used in this work is to maximize the data range in the parameter sweeps while keeping the engine stable. In practice, during the cold fast idle period, the timing is significantly retarded to accelerate the catalyst light-off time.

Operating points of interest are at fast idle (1200 rpm, 2 bar NIMEP), and points in the first acceleration of the FTP75; see Fig. 3. The following operating points are representative of those in the first acceleration: 1400 rpm, 4 bar NIMEP; 1600 rpm, 6 bar NIMEP; 1800 rpm, 8 bar NIMEP. Sweeps at constant speeds and loads are also done to assess the data trends.

The engine transient time scale in the first FTP acceleration is of the order of 2 to 5 seconds, which are long compared to the cycle times of 60 to 100 ms. However, the combustion surface temperature, which impacts the fuel film evaporation, is in transient responding to the load and speed changes. Therefore, it is cautioned that the static engine test would not reproduce the same PM emissions as in the actual test cycle. (See also comment at the end of the conclusion section.)

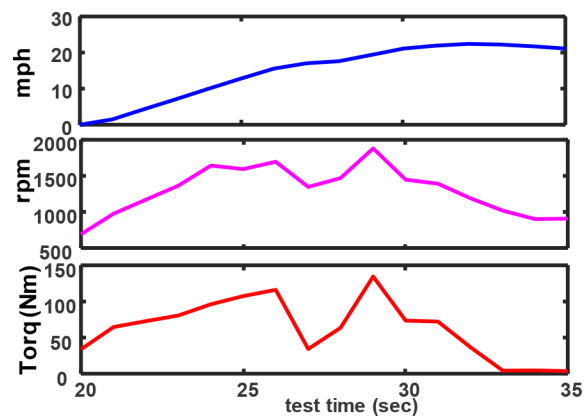


Figure 3. Operating condition of the first acceleration in FTP75; mid-size sedan (Ford Taurus vehicle).

GDI ENGINE BASELINE PN EMISSIONS AS FUNCTION OF SOI TIMING

To establish a baseline PN emission from the engine, a sweep of the start-of-injection (SOI) timing is done. The results at the fast idle condition (1200 rpm, 2 bar NIMEP) are shown in Fig. 4. There is a range of SOI timing (240 to 305 CAD ATDC-intake) for which combustion is deemed unstable (COV of NIMEP > 10%). With the late injection in this range, the charge is significantly stratified. Then the charge motion does not transport a mixture of the correct equivalence ratio to the spark plug; the process results in significant variations in the flame kernel development. The combustion becomes stable again with further retard of SOI when the charge motion convects the correct mixture to the spark plug. This phenomenon has also been observed in a similar engine [16].

The nucleation mode PN is relatively independent of SOI timing. This insensitivity suggests that the nucleation mode particles may not be related to the amount of in-cylinder liquid fuel, which changes substantially with the SOI timing. Since our focus is on the accumulation mode PN, the nucleation mode particles will not be further discussed. From here on, the PN are the values of the accumulation mode only.

For the accumulation mode, the PN is high with early injection and it drops rapidly (by more than an order of magnitude) with SOI at mid-stroke. Then it rises again when SOI is in the compression stroke. The high PN values with early injection (SOI between 0 to 30 CAD ATDC) are due to the significant wall liquid fuel film formed on the head resulting from the bounce of the fuel jet off the piston [16]. The rise of the PN with retarding SOI in the compression stroke is due to the decreasing time for fuel evaporation and mixing with the charge air [16].

The PN values as a function of SOI for other speed and load conditions are shown in Fig. 5. (Only the SOI range with stable combustion is shown.) The PN behaviors are similar to those under fast idle condition.