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Citation: Dimou, Iason, Kenneth Kar, and Wai Cheng. "Particulate Matter Emissions from a Direct Injection Spark Ignition Engine Under Cold Fast Idle Conditions for Ethanol-Gasoline Blends." SAE International Journal of Engines 4(1):1738-1746, 2011.

As Published: <http://dx.doi.org/10.4271/2011-01-1305>

Publisher: SAE International

Persistent URL: <http://hdl.handle.net/1721.1/87704>

Version: Author's final manuscript: final author's manuscript post peer review, without publisher's formatting or copy editing

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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).

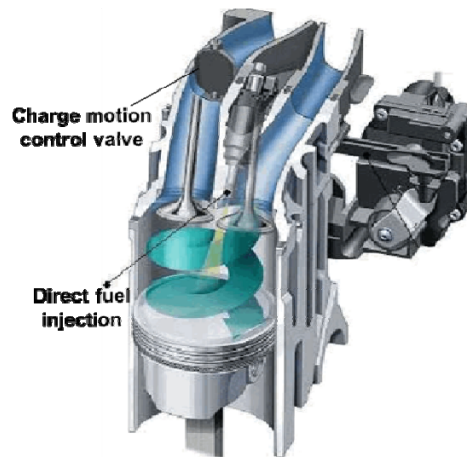


Fig. 1 – Charge motion control valve and injector arrangement. Under low load the charge motion control valve is close, providing a swirl motion to the intake air.

The 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.

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.

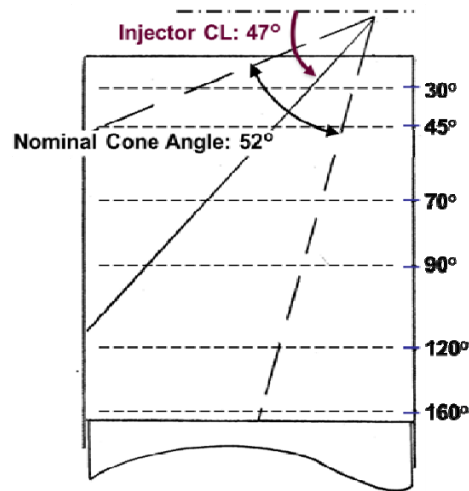


Fig.2 – Nominal Spray Geometry. The horizontal dotted lines mark the piston positions at the labeled values of crank angle after TDC.

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%

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.

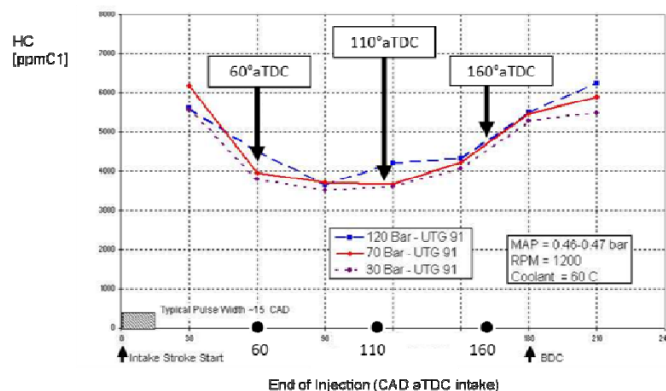


Figure 3 – HC emissions as a function of End-Of-Injection (EOI) time (as CA aTDC-intake); fuel pressure at 30, 70 and 120 bar [8].

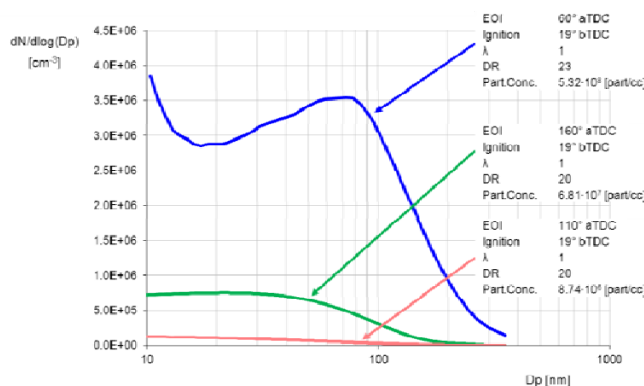


Figure 4 – PN distributions for EOI at 110° ATDC (intake) are an order of magnitude lower than 50° later or earlier. Engine at steady state: nimep = 3.8 bar, speed = 1,500 rpm, fuel: E0, fuel pressure = 70 bar, stoichiometric combustion ($\lambda=1$).

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 place 15 cm from the sampling point (Fig. 5). To avoid thermophoresis loss, the sampling tube is thermally insulated from its environment. The portion of the sampling tube exposed to the atmospheric air (5 cm long) is thermally insulated, using insulation material, and the portion of the sampling tube inside the dilution tunnel is thermally insulated from the dilution gas (N_2) with a gap between a ceramic tube and the sampling tube (Fig. 6). In this manner, the radial temperature gradient of the gas sample in the sampling tube is minimized.

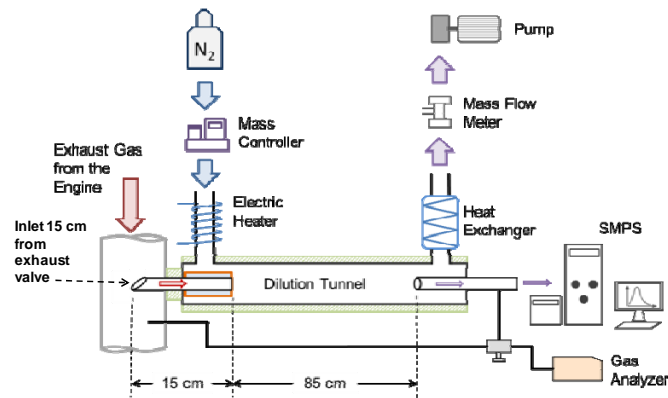


Figure 5 – The mini-dilution system designed for this project uses one dilution stage, with N_2 as diluter gas and a SMPS system to measure the PN distribution as a function of their electrical mobility equivalent diameter.

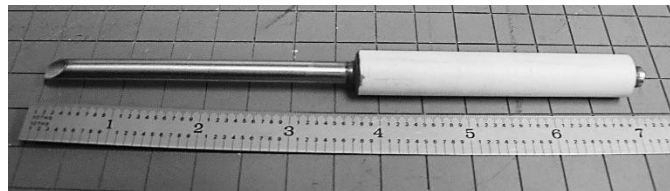
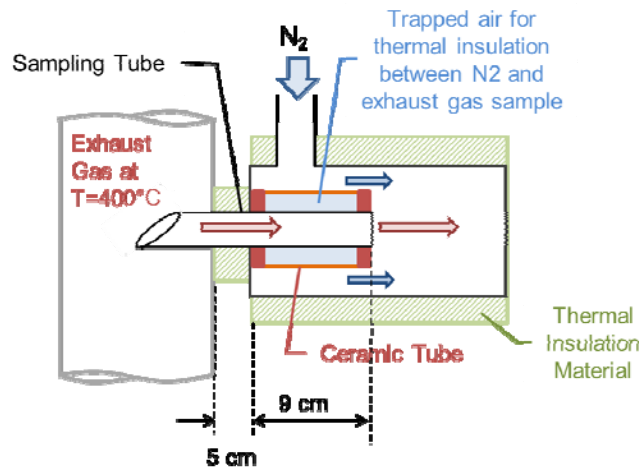


Figure 6 – In order to avoid PM losses due to thermophoresis, a ceramic tube trapped air between the sampling tube and the diluter flow, so the exhaust gas sample remained thermally insulated until the mixing point. The second picture shows the sampling tube before its installation.

The sample mixes with the N_2 in a tube (dilution tunnel) with diameter of 6.3 cm. A length of 85 cm allows sufficient time for the complete mixing of gases and a well developed flow to be established. At the end of the dilution tunnel, a small portion of the gas is fed to the SMPS and the rest is drawn out with a vacuum pump. The dilution tunnel is thermally insulated from the environment. With a gas temperature of 420°C at the sampling tube entrance and 30°C for the N_2 diluent, the measured temperature (35°C) at the dilution tube exit agrees (within a 5% error) with the calculated value for adiabatic mixing of the gases with the given flow rates. The theoretical calculated losses due to diffusion and thermophoresis in the dilution tunnel are less than 5%. Furthermore, the concentration/ temperature trajectory (assuming adiabatic mixing) of the mixture is sufficiently far away from the dew line that nucleation and condensation is negligible.

The flow and the amount of sampling gas have been maintained constant via a vacuum pump. In order to accurately control the sampling conditions (flow rates and temperatures) and to measure the dilution ratio, the following devices are used. A mass controller for the N_2 and an electric heater allows full control of the diluent (mass flow rate and temperature). A mass flow meter and a metering valve before the vacuum pump allow the control of the sample rate. For an accurate calculation of the dilution ratio (DR), a HORIBA

MEXA-554JU gas analyzer measures the CO₂ concentrations of the raw exhaust sample and the diluted gas sample just before entering the SMPS. Since the gas analyzer accepts only dry sample, the measured CO₂ concentrations are corrected for water content. Thermocouples at selected locations measure the temperatures of the gases throughout the apparatus.

SAMPLING SYSTEM VALIDATION

Before the actual measurements, a series of tests have been conducted and an experimental protocol is established to validate the SMPS and the mini-dilution tunnel performance. The operational parameters for the SMPS are: 7 LPM Excess and Sheath Air and 0.7 LPM Monodisperse Air (ratio: 1 to 10). (The terminologies are those of the SMPS operation: the former quantity refers to the DMA outflow which does not enter the CPS; the latter, to the flow into the CPC.) The selected flow rates correspond to a PM electrical mobility equivalent diameter (D_p) range between 15 and 350 [nm]. The variability of these flows during the measurements is less than 5%.

In order to choose the sampling conditions (gases flow rates, N₂ temperature, etc) a series of experiments have been conducted. During these experiments the engine run under the conditions described in table 3. These conditions have been chosen to ensure a stable engine operation and lower PN than those of the actual tests, which are conducted at lower ECT. Successful measurement at the lower PN values would guarantee sufficient instrumental sensitivity. Due to the short length of the sampling tube (Fig. 5), the most significant parameters affecting the PM losses in our process is the DR and the temperature of the N₂. Figures 7 and 8 show the PN distribution curves when these two parameters are varied. According to the results of these experiments, a DR more than 15 does not affect significantly the PN distribution. Also, a N₂ temperature within a range of 30 to 300°C does not have significant effect on the PN distribution. Other studies that sampled from the exhaust tailpipe of the car in order to investigate PN distribution (with exhaust gas temperatures are in the order of 150-200°C), suggest that the chosen temperature of the diluted gas plays an important role for an accurate measurement. In this case, during the dilution process the temperature of the sample exhaust gas is in order of 420°C and is reduced to 40°C fast enough so that the gas does not cross the dew curve and does not suffer from condensation effects that could change the PN distribution. Finally, a DR in the order of 30 ensures that there are no losses due to nucleation and coagulation.

Table 3 – Engine operational conditions during the sampling system validation process.

Fuel	E0 (Gasoline)
Speed	1,500 rpm
nimep	3.8 bar
Coolant Temperature	80 °C
End of Fuel Injection	120° aTDC-intake
Spark Ignition	19° bTDC
Fuel Pressure	70 [bar]
λ	1

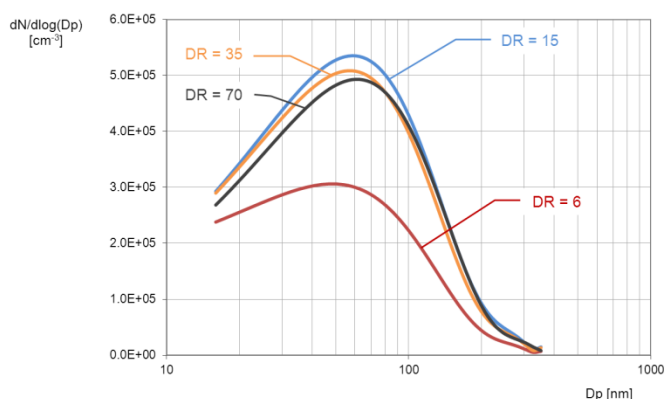


Figure 7 –PN distribution for different dilution ratios. Temperature of the N₂ diluent is 35°C and the engine conditions are as described in table 3.

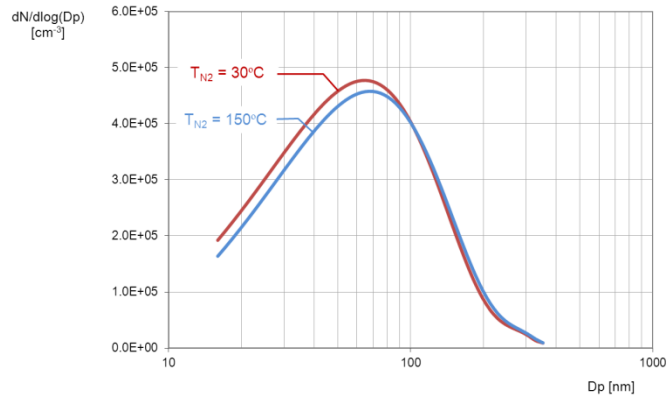


Figure 8 –By varying the Nitrogen Temperature, there is no significant difference for Temperature range from 30 to 150°C. During these measurements the Dilution Ratio was 58. Engine Conditions as described in table 3.

Table 4 – Sampling System Operational Conditions.

N ₂ Flow rate	30 SLPM (±0.3 SLPM)
N ₂ Temperature	30 °C (±2°C)
SMPS Sample Flow rate	0.7 LPM (±0.1 LMP)
Pump Flow rate	23.5 SLPM (±0.3 SLPM)

OPERATING PROCEDURE

In order to ensure that the sampling system is clean before each experiment, the system is purged by hot N₂ until the SMPS measurement shows a PN density of less than 20/cm⁻³ throughout the Dp range. Usually this process takes less than 10 [min].

The measurements have been obtained under steady state cold fast idle condition. The fuel and lubricant temperatures are kept at the selected values by the refrigeration and heating water circuit. A 5-10 min running time before each measurement is needed to stabilize the running condition. For a single PN distribution curve, the SMPS needs 1.5 min for a scan. The distribution curves presented in the following are the averages of a minimum of 10 scans. During this time, the gas analyzer measures the engine out CO₂ and that at the entrance of the SMPS (Fig. 4) so that a dilution ratio could be calculated. Each data set takes approximately 25 min to acquire.

RESULTS

The PN distributions presented in this section are obtained at simulated cold-fast-idle conditions (Table 5). The results are organized in two sections: the coolant temperature effects on PN distribution for different fuels, and the fuel effect on the total PN density.

Table 5 – Engine's Operating Parameters

Engine Speed	1,200 [rpm]
nimep	1.5 [bar]
COV of gimep	< 4%
End of Fuel Injection	120° aTDC (intake)
Spark Ignition	15° bTDC (compression)
Fuel Pressure	70 [bar]
λ	1

ENGINE COOLANT TEMPERATURE EFFECTS ON PN DISTRIBUTION

The PN distributions for gasoline (E0) at engine coolant temperatures (ECT) from 0 to 40° C are shown in Fig. 9. The general shape of the distribution is monotonic decrease in PN as the particle size increases. No bi-modal distribution is observed. The shape is different from that obtained from exhaust sampling, for which a local peak at the larger D_p is observed due to agglomeration [5, 6]. There is no significant change in PN with respect to ECT for particles larger than 200 nm. For the small particles (< 100 nm), the PN increases modestly as the ECT drops from 40° to 20° C. The increase becomes much more drastic when the ECT falls below 15° C. This rapid increase in PN at the lower temperatures may be attributed to the significant reduction of fuel evaporation at these temperatures so that there is substantial liquid fuel impingement on the cylinder wall. (The effect is non-linear with respect to temperature because of the exponential vapor pressure- temperature dependence.) The fuel vapor evaporated from the wall fuel film mixes slowly with the charge air to form pockets of fuel rich mixture. When the flame arrives, these rich pockets are engulfed by the high temperature burned gas, and they are pyrolyzed to form PM.

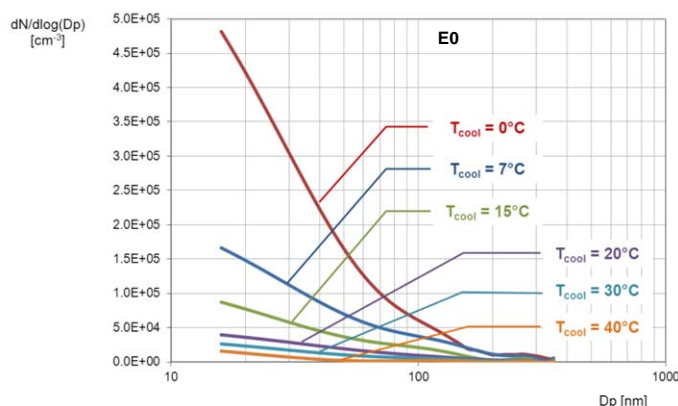


Figure 9 – PN distributions for gasoline (E0) at different ECT.

The PN distributions for E10 (10% ethanol; 90% gasoline by volume) at different ECT are shown in Fig. 10. The x- and y- scales used in Fig. 9 and 10 are the same so that the distributions can be visually compared. The PN distributions at the higher temperatures (>20° C) are similar, both in shape and in values, to those obtained with E0. At lower temperatures, however, the PN values are substantially lower. Since the evaporative properties of the fuel should not have changed drastically with the 10% ethanol, we have attributed the PN suppression to be attributed mainly to the effect of ethanol on the PM formation chemistry. This point will be discussed in a later section on determining the threshold of ethanol content in the gasohol for PM formation.

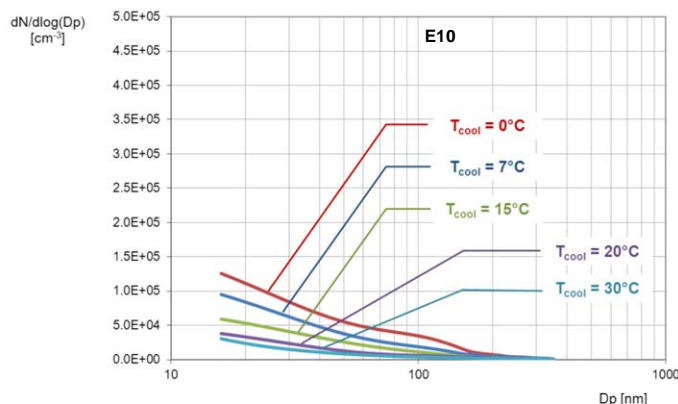
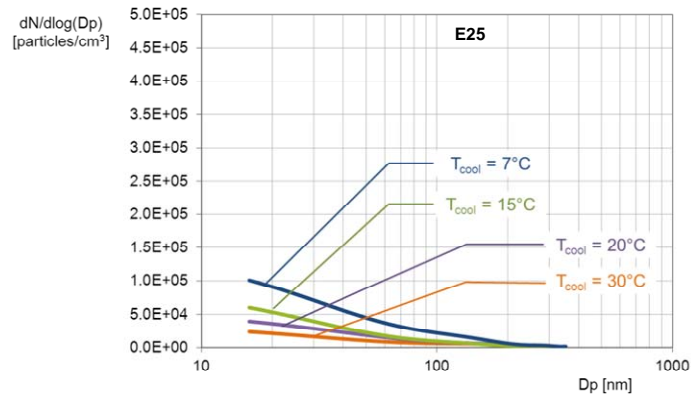
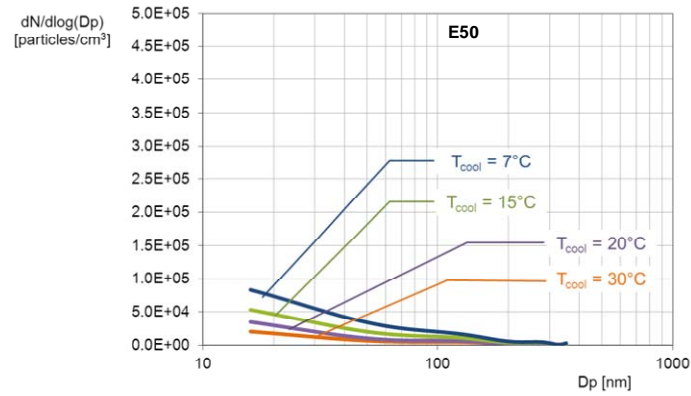


Figure 10 –PN distributions for E10 (10% ethanol – 90% gasoline) at different ECT.

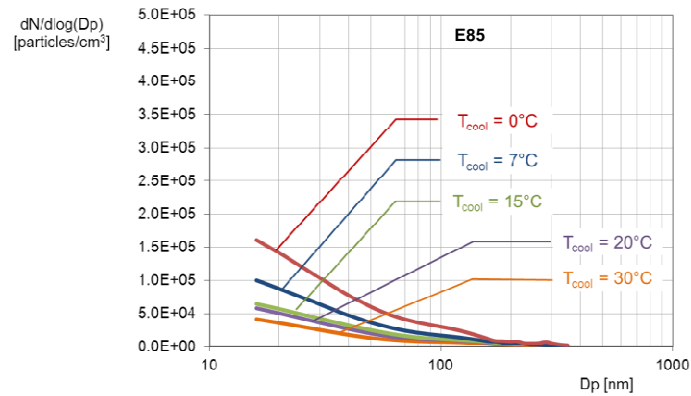
The PN distributions for E25, E50 and E85 at different ECT are shown in Fig. 11. (Data at 0° C ECT have been obtained only for E85.) The x- and y- scales are the same as those of Figures 9 and 10. Comparing Fig. 10 and 11, the PN distributions are almost the same (in shape and in values) for gasohols with ethanol content $\geq 10\%$.



(a)



(b)



(c)

Figure 11 – PM distributions for Fuel Blends: (a) E25 , (b) E50, and (c) E85 at different ECT.

Previous research [7] has indicated that the PN emitted from DISI engines are strongly correlated to the amount of aromatics present in the fuel. Thus, with an increase of ethanol content in the fuel, the fraction of aromatics is reduced, and hence the PN values. For a fuel change from E10 to E85, the aromatic content (in liquid volume) changes from 26.1% to 4.35%. The data in Figures 10 and 11, however, show that the PN values are essentially independent of the fuel ethanol content. Thus the aromatic displacement effect would not be a significant factor in explaining the behavior.

TOTAL PN EMISSIONS

The total PN/cm³ emitted from the engine can be calculated by direct integration of the curves presented above. The integration is over the SMPS range of 15 nm to 350 nm. Figure 12 shows the total PN emitted from the engine running with E0, E10, E25, E50 and E85 as a function of ECT. The data agree well with an exponential fit to the ECT (coefficients of determination for all fits have R²>95%). The results here show, consistent with the PN distribution results, that for ECT higher than 20° C, the total PN emissions are almost independent of the ethanol content in the fuel. However, at lower ECT (<20° C), there is a large drop (by a factor of more than 3 at 0° C) in total PN in going from E0 to E10. Thus a small increase in fuel ethanol content in the fuel can substantially change the PN values when ECT is less than 20° C.

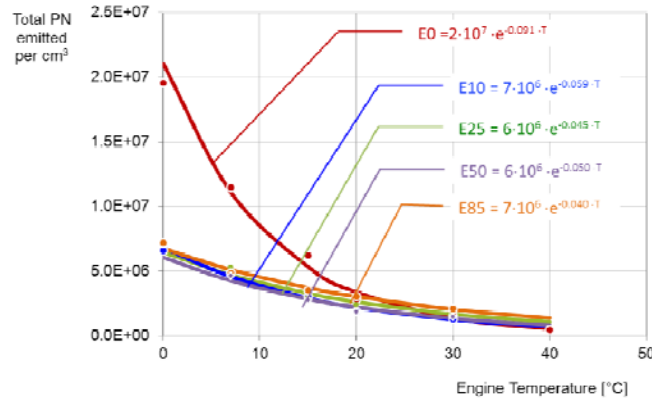


Figure 12 – Total PN emissions in the 15 to 350 nm range as a function of ECT for different gasohol fuels. The solid lines are exponential temperature fits (with T in °C) to the data.

To investigate the threshold of ethanol content which would significantly change the PN values at low ECT, the experiments have been repeated with E2.5 and E5 (corresponding to 2.5 and 5% ethanol by volume in the fuel). The results are shown in Fig. 13, together with the E0 and E10 results from Fig. 12. The data show that the rapid decrease in PN occurs when the ethanol content is increased from zero to 10%. This effect is more evident with the data at a selected temperature. The PN as a function of ethanol content at 0° C is shown in Fig. 14, which shows the major PN reduction from E0 to E10. There is very little improvement beyond E10 (Fig. 12). The midpoint of the PN change occurs at approximately E5.

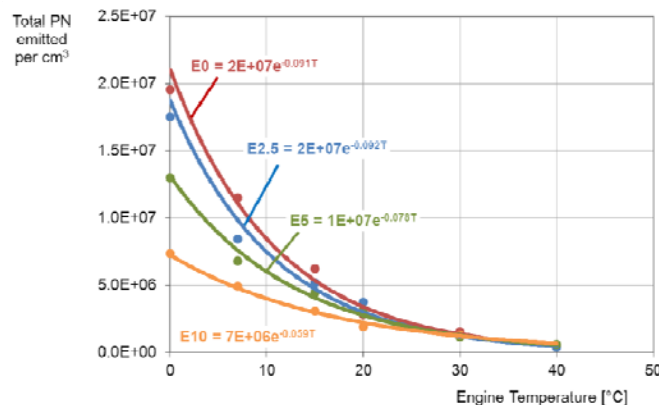


Figure 13 – PN emissions in the 15 to 350 nm range as a function of ECT for E0, E2.5, E5, and E10. The solid lines are exponential temperature fits (with T in °C) to the data.

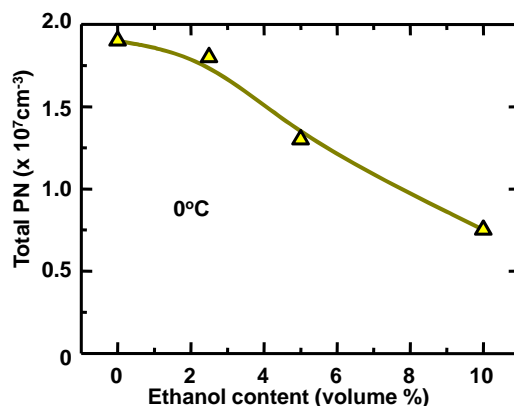


Figure 14 – PN emissions in the 15 to 350 nm range at 0° C ECT as a function of fuel ethanol content.

SUMMARY/CONCLUSIONS

A mini-dilution tunnel coupled with an SMPS system has been used to measure the effects of ethanol-gasoline fuel blends (in the range of E0 to E85) on PM number emissions at ECT from 40° C to 0° C in a Direct Injection Spark Ignition (DISI) engine under cold fast idle condition. The focus is on engine-out emission, so that samples are collected at a short distance (15 cm) from the exhaust valve. The following observations are made.

1. A monotonic PN distribution with values decreasing with increase of particle size is observed for all the fuels and at all the ECT tested. The local peak (identified as due to particle agglomeration) which has been observed in tailpipe sampling is not observed.
2. For gasoline (E0), the PN values for D_p less than 100 nm increase with decrease in ECT. The change is modest for ECT change from 40° C to 20° C. The increase, however, is substantially larger when ECT is lower than 15° C. This observation is attributed to the non-linear dependence of evaporation to temperature.
3. For E10 to E85, the shape of the PN distribution is similar to that derived from E0. There is, however, only a modest increase in the PN values when ECT is changed from 30° C to 0° C. Furthermore, both the shape and values of the distribution at the same ECT are insensitive to the alcohol content in the fuel. Thus at low ECT, there is a sharp drop of PN from E0 to E10, but further increase in ethanol content does not produce any further PN changes.
4. At ECT above 20° C, the total PN (integrated over the distribution from 15 to 350 nm) is insensitive to the fuel ethanol content.
5. At ECT < 20° C, the total PN for E10 to E85 are almost identical, and the values increase modestly with decrease of ECT. For E0, however, the PN values are substantially higher; e.g. at 0° C ECT, the total PN emission from E0 is more than 3 times that from E10. Thus there is a substantial change in PN emissions when the fuel is changed from E0 to E10, and very little change is observed with further increase in ethanol content from E10 to E85.
6. The above observation is confirmed by emissions measurements with E2.5 and E5. The midpoint of the change in total PN value from E0 to E10 occurs approximately at E5.
7. Because the evaporative property of the fuel does not change significantly from E0 to E10, the substantial reduction in PN with ethanol is attributed to the effect of ethanol on PM chemistry.

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ACKNOWLEDGMENTS

This work was supported by the MIT Consortium for Engine and Fuels Research; the members are Ford, GM, Saudi Aramco, and VW.

DEFINITIONS/ABBREVIATIONS

CA	Crank angle
COV	Coefficient of variation
CPC	Condensation particle counter
E0, ..., E85	Denotes ethanol volume percentage in fuel
ECT	Engine coolant temperature
EOI	End of injection
DMA	Differential mobility analyzer
DISI	Direct injection Spark ignition
D_p	Mobility diameter
DR	Dilution ratio
gimep	Gross indicated mean effective pressure
HC	Hydrocarbon
nimep	Net indicated mean effective pressure
PFI	Port-fuel-injection

PM	Particulate matter
PN	Particulate number
SMPS	Scanning mobility particle sizer