

Particulate Matter Sampling and Volatile Organic Compound Removal for Characterization of Spark Ignited Direct Injection Engine Emissions

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ABSTRACT

More stringent emissions regulations are continually being proposed to mitigate adverse human health and environmental impacts of internal combustion engines. With that in mind, it has been proposed that vehicular particulate matter (PM) emissions should be regulated based on particle number in addition to particle mass. One aspect of this project is to study different sample handling methods for number based aerosol measurements, specifically, two different methods for removing volatile organic compounds (VOCs). One method is a thermodenuder (TD) and the other is an evaporative chamber/diluter (EvCh). These sample handling methods have been implemented in an engine test cell with a spark ignited direct injection (SIDI) engine. The engine was designed for stoichiometric, homogeneous combustion. SIDI is of particular interest for improved fuel efficiency compared to other SI engines, however, the efficiency benefit comes with greater PM emissions and may therefore be subject to the proposed number based PM regulation. Another aspect of this project is to characterize PM from this engine in terms of particle number and composition.

PM number distributions were acquired using a TSI Scanning Mobility Particle Sizer (SMPS). For the operating conditions considered, PM number distributions have a large accumulation mode (30-294 nm) but a very small nucleation mode (8-30 nm). This small nucleation mode is

understood to represent a lack of condensation particles meaning that neither the exhaust conditions nor the sample handling conditions are conducive to condensation. This lack of nucleation mode does not, however, represent a lack of VOCs in the sample. It was found, using mass spectral analysis (limited to PM>50 nm), that PM from the SIDI engine has approximately 40% organic content through varying operating conditions. This raises the question of how effective different sample handling methods are at removing these VOCs.

For one specific operating condition, called Cold Start, the un-treated PM was 40% organic. The TD reduced the organic content by 7% while the EvCh reduced it by 13%. For other operating conditions, PM treated for volatile removal actually exhibited an increase in organic fraction on the order of 5%. This addition with the TD appears to be sensitive to the gaseous hydrocarbon concentrations in the exhaust. Based on the remaining organic content while using a VPR, it has been concluded that PM emissions from the SIDI engine contain VOCs which are tightly bound to the solid carbon PM structure.

INTRODUCTION

Vehicular PM has long been regulated based solely on mass. Since the first PM regulations were put in place, we better understand the deposition of aerosols in specific parts of the

human respiratory system [1]. Small particles contribute very little to total PM mass but can penetrate the body's defenses [2]. This aspect of small particles has garnered the attention of regulatory bodies seeking the most effective way to mitigate health impacts. It has been proposed that PM should be regulated by measuring the number of individual particles as well as the total mass of all particles [3].

The Particle Measurement Programme (PMP) is a regulatory effort wherein the European Union is seeking the best method for measuring PM based on number [3,4]. This has been a formidable challenge because the nature of PM is very sensitive to sample handling. The formation of condensation particles (condensed VOCs) can be highly dependent on the temperature and pressure history of the exhaust sample. Research on diesel engine emissions has shown that PM in the smaller size range (<30 nm) is dominated by condensation particles which can significantly increase the total PM number while having little effect on total PM mass [4]. This sensitivity to condensation particles is an important factor in making repeatable PM number measurements. To address this sensitivity, PMP has proposed two main ideas for the PM number measurement protocol [3, 5]. The first is to limit the particle count to particles greater than 23 nm and the second is to install a volatile particle remover (VPR) which is meant to remove VOCs from the sample [3, 5].

One major objective of this project is to study the removal of VOCs from an exhaust sample. It is an interesting topic because there are two different types of VPR seen in PMP studies [3, 5], the effects of which are not completely understood. The engine test cell has been fitted with these two VPR systems. The arrangement of the aerosol sampling system allows sampling through either VPR device or bypassing both. This paper shows the effect of each VPR on the VOC content in PM. For this comparison, the engine specified in the following paragraph was used to generate a range of PM through different operating conditions.

The other objective of this project is to characterize PM emissions from a spark ignited direct injection (SIDI) engine in stoichiometric, homogeneous operation. SIDI engines are becoming more available in the global marketplace due to their favorable fuel consumption and cost characteristics. There is currently a limited data base on PM emissions characteristics of SIDI engines. As a result, one objective of this project was to add to this PM data base thus providing the OEMs better

understanding to enable reductions in the PM signature of these engines.

The PARTICULATES programme was a three year study to quantify PM emissions for three different engine technologies: diesel (with and without DPF), gasoline port fuel injection (PFI), and SIDI. Both mass based and number based PM measurements were made. According to PM mass emissions results, the SIDI vehicle performs almost as well as a diesel vehicle that has a diesel particulate filter (DPF) [4]. This engine technology comparison is quite different in terms of PM number. The SIDI vehicle emits greater PM numbers than gasoline PFI vehicles and diesel vehicles with a DPF [4]. Measurements made in [4] substantiate the need for a better understanding of PM emissions from SIDI engines.

Pending regulation on PM number means this phenomenon needs to be better understood. It is also clear that the sampling systems need to be carefully controlled to make sure measurements are representative of what the engine is producing. This emphasis on the PM sampling system ties into the PMP proposal for a number based sampling protocol, including two proposed methods for removing VOCs.

EXPERIMENTAL SETUP

This section describes the equipment used for making detailed PM measurements starting with the SIDI engine. The TD and EvCh will then be discussed followed by the instrumentation used.

Figure 1 shows a simple schematic of this equipment in roughly the same configuration as in the test cell.

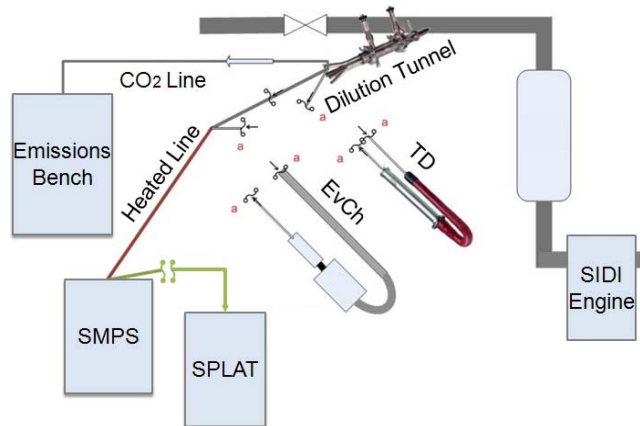


Figure 1: Diagram of the experimental setup

ENGINE

Design of the SIDI engine was provided by

General Motors and uses a direct-injection cylinder head. The spark plug is centered about the four valve ports, a pressure transducer is located on the side between the intake and exhaust valve ports, and the fuel injector is positioned between the intake valve ports, angled into the cylinder. *Table 1* lists the overall specifications of the single-cylinder SIDI engine.

Table 1: SIDI engine specifications

Compression Ratio [-]	11.97	
Bore [in, mm]	3.3842	85.96
Stroke [in, mm]	3.72	94.6
Displacement [in ³ , cm ³]	32.89	549
Clearance Volume [in ³ , cm ³]	3.05	50
Connecting Rod Length [in, mm]	6	152.4
Intake Valve Open [°ATDC]	350	
Intake Valve Close [°ATDC]	580	
Intake Valve Lift [mm]	9.9	
Exhaust Valve Open [°ATDC]	150	
Exhaust Valve Close [°ATDC]	365	
Exhaust Valve Lift [mm]	9.9	

Piston

The piston was designed for compression ratio 11.97:1. It has a relatively simple shape that is consistent with homogeneous charge SIDI. Lean stratified SIDI generally requires a piston contoured to guide an injection spray toward the spark plug. The engine used for this project was not designed for lean stratified combustion although some operating conditions push the limit between homogeneous and stratified charge operation.

Fueling

The fuel used for this project is EPA Tier II EEE with a research octane number of 96.5 and an aromatic content of 28%. Fuel is injected into the cylinder at high rail pressure (11 MPa) through a Bosch single-hole injector. The injector has the following specifications: 70° spray angle, 0° offset, and 15cm³/s nozzle. Fuel was injected in a single pulse and the fueling rate was set by defining the injection duration (on the order of 2 milliseconds). Injection timing is specified by the engine crank angle corresponding to the end of the injection pulse termed end of injection (EOI).

Experimental Matrix

Multiple steady state test conditions were chosen to represent different operating conditions experienced by the engine in a vehicular application. The engine speed was 2000 rpm with a nominal load of 320 kPa IMEP which is typical

of conditions encountered during emissions driving test cycles. Parameters used to define different operating conditions are shown in *Table 2*. Most operating conditions consist of one parameter that deviates from the Baseline (highlighted in *Table 2*). This was done to isolate the effect of each parameter. Only select results from this experimental matrix are presented in this paper (more can be found in [6, 7]).

Table 2: Experimental matrix for operation at 2000 rpm and a nominal 320 kPa IMEP (limited results from grayed test points are included in this paper).

Name	End Of Injection	Fuel	AF	Spark Advance	Injection Pressure	Intake Temp
Units	[°bTDC]	[mg/cycle]		[°bTDC]	[MPa]	[°C]
Baseline	280	11	15	25	11	45
Early EOI	330	11	15	25	11	45
Late EOI	100	11	15	25	11	45
Medium Load	280	16	15	23	11	45
Heavy Load	280	21	15	18	11	45
Lean	280	11	17	25	11	45
Rich	280	11	13	25	11	45
MBT-15	280	11	15	10	11	45
Medium Rail Pres	280	11	15	25	8	45
Low Rail Press.	280	11	15	25	4	45
Cold Start	80	11	15	25	11	25
Hot Firing	80	11	15	25	11	90

AEROSOL SAMPLING

The aerosol sampling system is not an exact replica of the reference system used for the PMP Light Duty Inter-Laboratory Exercise [3] but uses the same guiding principles. The primary difference is that the PMP study [3] uses a constant volume sampler (CVS tunnel) which dilutes all of the vehicle exhaust and then samples it for analysis. This PMP system is called a full flow dilution system whereas the one used for this paper is a partial flow dilution system as described below.

Dilution

The partial flow dilution system is a Dekati FPS-4000 mini dilution tunnel (MDT). Unlike the CVS tunnel, a sample is drawn directly from the raw exhaust stream and is handled under controlled conditions. The sample is drawn through a heated probe set to 250°C, similar temperature to the raw exhaust. It then passes through two stages of dilution in the MDT; primary dilution through a perforated tube diluter with clean, dry dilution air at 200°C and then secondary dilution through an ejector diluter with un-heated dilution air. This dilution method has been optimized at the UW Engine Research Center to measure engine-out emissions. Thus is the fundamental difference from the PMP full flow dilution system which is

optimized to measure tailpipe emissions as they mix with the atmosphere. Henceforth, engine-out emissions are used to characterize the SIDI engine at different operating points and to compare VPR systems.

Dilution ratio was measured by comparing the CO₂ concentrations in the raw exhaust and in the diluted sample. Accounting for the ambient CO₂ concentration leads to the following calculation: $DR = (CO_{2\text{raw}} - CO_{2\text{amb}}) / (CO_{2\text{diluted}} - CO_{2\text{amb}})$. The combined dilution ratio for both stages of dilution within the MDT was approximately 10:1.

As noted earlier, the experimental system allowed the diluted sample to be treated by either VPR. As an experimental control, there was also a section of normal sample line (heated, 1/2 in, stainless) that could be put in place to bypass both VPRs. The VPR systems and their implementation for this research are described in more detail below.

Thermodenuder (TD)

The Dekati Thermodenuder used in this research, depicted schematically in *Figure 2*, consists of a heater section and a denuder section. Heating the sample is a mechanism by which the VOCs are evaporated from the PM. The heater was set to 275°C. Following passage through the heater section, the sample is then passed through the denuder section which contains activated charcoal used to adsorb the evaporated VOCs from the sample. This process is facilitated by cooling air as seen in *Figure 2*. The flow rate of cooling air was controlled such that the cooling air outlet temperature was less than 50°C, as specified by Dekati [8]. Dekati also specifies an optimal sample flow rate of 15 l/min which was controlled downstream prior to analysis. Although not obvious from the schematic in *Figure 3*, the cooling air does not mix with the sample.

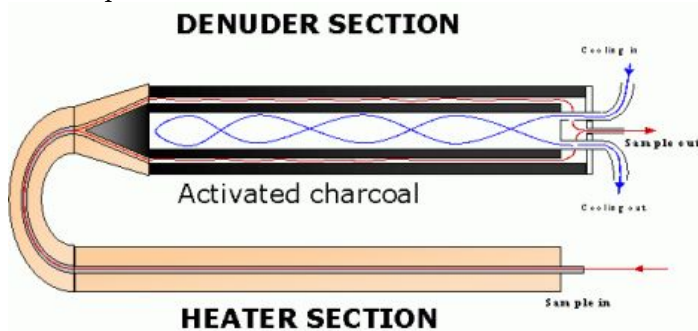


Figure 2: Schematic of a Dekati Thermodenuder [8]

Evaporative Chamber and Secondary Diluter (EvCh)

Similar to the TD, the EvCh system (*Figure 3*) heats the sample to 275°C as a mechanism to evaporate VOCs. Rather than using activated charcoal to remove VOCs, the EvCh dilutes the sample again in order to reduce the partial pressure of gaseous VOCs. With a lower partial pressure they are not expected to re-condense and form condensation particles prior to number counting. The configuration is shown in *Figure 3*. The primary design constraint for this configuration was to achieve a sample temperature of 275°C immediately before dilution. A pre-heating line set to 275°C and an evaporative chamber set to 500°C were used to achieve the desired temperature. A Dekati Diluter was used which is an ejector diluter with a dilution ratio of approximately 10:1. This precise dilution ratio was measured using CO₂ in the same method as for the MDT. The sample out flow rate was set to 15 l/min, the same as for the TD.

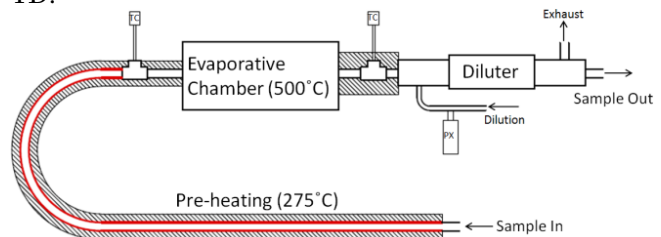


Figure 3: Schematic of the EvCh

The EvCh is very much like the PMP reference system as seen in [3] with the main difference being the temperature control method. The PMP reference system used the evaporative chamber set to 300°C with a residence time of ~0.2 seconds [3]. The EvCh system, on the other hand, was setup based on the sample temperature as measured immediately prior to the diluter. The inclusion of a pre-heating line and a hotter evaporative chamber temperature is expected to meet or exceed the effectiveness of the PMP reference system in terms of VOC evaporation, while being comparable to the TD in terms of heated residence time (~0.6 seconds) and sample temperature (275°C).

EMISSIONS INSTRUMENTATION

TSI Scanning Mobility Particle Sizer (SMPS)

Stainless steel sample lines, heated to 45°C, carry the sample to a TSI SMPS (specifics: 0.17 mm impactor inlet pre-classifier impactor, TSI 3080 Electrostatic Classifier, TSI 3081 Differential Mobility Analyzer, and TSI 3010 Condensation Particle Counter). The SMPS takes size resolved PM measurements on the