

Exploration of Semi-Volatile Particulate Matter Emissions from Low Temperature Combustion in a Light-Duty Diesel Engine

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ABSTRACT

Diesel low temperature combustion (LTC) is an operational strategy that is effective at reducing soot and oxides of Nitrogen (NO_x) emissions at low engine loads in-cylinder. A downside to LTC in diesel engines is increased hydrocarbon (HC) emissions. This study shows that semi-volatile species from LTC form the bulk of particulate matter (PM) upon dilution in the atmosphere. The nature of gas-to-particle conversion from high HC operating modes like LTC has not been well characterized. In this work, we explore engine-out PM and HC emissions from LTC and conventional diffusion combustion (CC) operation for two different engine load and speed modes using a modern light-duty diesel engine. An experimental method to investigate PM volatility was implemented. Raw exhaust was diluted under two dilution conditions. A tandem differential mobility analyzer (TDMA) was used to identify differences in volatility between particle sizes. The study revealed that LTC PM mass and number concentration showed a greater dependence on dilution conditions than PM from CC. There was also evidence of differences in particle volatility as a function of particle size for PM from LTC, with PM from CC having more consistent volatility characteristics. The results of this study show that significant semi-volatile PM emissions are present in LTC exhaust compared to CC operation though they are highly dependent on dilution conditions. This indicates that gas-to-particle conversion processes require additional study to identify the clear impact of LTC implementation on real-world PM emissions.

CITATION: Lucachick, G., Avenido, A., Kittelson, D., and Northrop, W., "Exploration of Semi-Volatile Particulate Matter Emissions from Low Temperature Combustion in a Light-Duty Diesel Engine," *SAE Int. J. Engines* 7(2):2014, doi:10.4271/2014-01-1306.

INTRODUCTION

High power density, reliability, and efficiency of the internal combustion engine have made it the primary source of mobile mechanical power in industrial societies. This widespread use has led to ever-greater motivation to improve its efficiency and emissions characteristics. The aggressive trajectory of the corporate average fuel economy (CAFE) standards combined with the rising cost of fuel and the threats of climate change from CO₂ emissions continue to force engine manufacturers to improve fuel economy. The better inherent efficiency of diesel engines versus spark ignition engines has recently led to increased sales of diesel powered passenger vehicles. Unfortunately, diesel vehicles must use costly aftertreatment systems to meet increasingly stringent regulations on traditional pollutants like particulate matter (PM) and oxides of Nitrogen (NO_x). Aftertreatment systems increase cost, and have limited the penetration of diesel passenger vehicles in the marketplace.

Partially premixed diesel low temperature combustion (LTC) is being investigated as a strategy to reduce the need for diesel aftertreatment systems, with a small fuel economy penalty.

This combustion strategy is enabled by high rates of cooled exhaust gas circulation (EGR) to extend ignition delay and high injection pressure to create a primarily premixed combustion event. As a result, both rich zones in the combustion chamber responsible for soot production and high temperature regions responsible for NO_x production are avoided. In this study two LTC strategies similar to those used by by Knafl et al. [1] are implemented: Early LTC (ELTC) is a strategy that uses a single early injection, with peak cylinder pressure occurring near TDC. In the study by Knafl, ELTC maximum load has been shown to be limited to 2 Bar brake mean effective pressure (BMEP) because as fueling increases, the risk of diesel knock rises in tandem with increasing peak temperatures and pressures near TDC. Late LTC (LLTC) uses a single late injection, and is suitable for higher loads. Because of the late injection, combustion is centered after TDC, reducing peak temperatures and pressures. This type of combustion has been shown to be stable up to 7 Bar BMEP.

Despite its attractiveness, LTC has been shown to significantly increase hydrocarbon (HC) emissions compared with conventional diffusive combustion (CC) in diesel engines. Jacobs et al. [2] reported about 10% of the total HC emissions

and 20 times the amount of CO for LTC versus CC at the same engine speeds and loads. Sluder et al. [3] found increased CO, and slightly increased HC when comparing a high EGR, high fuel rail pressure combustion mode to a CC mode.

A recent study by Northrop et al. [4] suggested that unburned HC from LTC used in low engine load operating conditions have the potential to form volatile PM in higher concentrations than CC due to gas-to-particle conversion. Storey et al. [5] showed that almost 90% of the PM mass was comprised of organic species in a study of premixed charge compression ignition. Species of concern for gas-to-particle conversion include low volatility fuel species and lubricating oil, as well as partially-reacted higher molecular weight products of combustion like polycyclic aromatics. More recently, organic acids have also been identified as potential PM contributors [6]. As shown in the results of this study, upon dilution, these species undergo gas-to-particle conversion by formation of new volatile nucleation mode particles, and also by accumulating on existing PM.

Higher HC and CO emissions from LTC combustion can poison a diesel oxidation catalyst (DOC), and inhibit the removal of these species [7]. In the gas form, semi-volatile HCs are not collected by diesel particulate filters. Therefore, higher than desirable PM emissions can form in the primary exhaust plume downstream of aftertreatment catalysts meant to eliminate them [8]. The volatile nature of PM from LTC makes characterization difficult. In a recent study conducted by Kolodziej et al. [9], three methods were used to determine elemental versus organic carbon (EC/OC) ratios for LTC. For a 5.5 Bar IMEP ELTC mode similar to the one conducted in this study, they found the resulting EC/OC ratios as follows: 0.11 for NIOSH method 5040, 0.24 for ORNL microwave extraction, and 5.1 for Horiba Mexa Analyzer. Such differences in measured EC/OC highlight the challenges facing researchers in characterizing PM from LTC.

Most of the difficulty in determining the quantity and composition of semi-volatile PM in LTC exhaust relates to how extracted samples are collected, stored and pre-treated. For example, evaporation of semi-volatile compounds from a filter prior to analysis can lead to significant errors in measured concentration. The objective of this study is to characterize semi-volatile PM from LTC operating modes using online aerosol processing techniques that give results in near real-time, thus reducing experimental errors. It compares PM from a light-duty diesel engine operating in LTC and CC modes. Characterizing such emissions is important for accurately quantifying the evolution of low volatility HC emissions from LTC and predicting their behavior in the primary exhaust plume.

EXPERIMENTAL

Engine Setup

This study was performed using a modern 2.0 liter turbocharged direct-injection compression ignition engine manufactured by General Motors with the specifications shown in Table 1. This engine is factory equipped with a variable geometry turbocharger, variable swirl actuation, and high pressure common rail fuel injection. The engine was controlled with National Instruments hardware using a fully configurable Driven engine control unit. This engine is equipped with a modified EGR system that allows greater control of EGR temperature than the stock EGR system. An aftermarket PID controlled water/air after-cooler provides improved control of intake manifold temperature. Ultra low sulfur #2 diesel (ULSD) was used for the duration of the study with properties displayed in Table 2.

Table 1. Engine specifications

Number of cylinders	4
Displacement	1956 cc
Bore	83.0 mm
Stroke	90.4 mm
Compression ratio	16.5
Output @ engine speed kW/rpm	117.3/4000
Torque @ engine speed Nm/rpm	259 / 1750
Bosch Solenoid Injector Hole Quantity	7

Table 2. ULSD Fuel Specifications

ULSD 0% Biodiesel Fuel Properties	
Density (15.56 °C)	0.8517
Kinematic Viscosity mm ² /sec	2.399
Lower Heating Value	42.792 MJ/kg
Cetane #	41.1
Carbon (Wt%)	86.99
Hydrogen (Wt%)	13.01
Oxygen (Wt%)	<.05%
Sulfur (ppm)	4.8
ASTM D86 distillation results:	
Percent Recovery	Temperature (°C)
10%	210.94
20%	225.28
30%	237.50
40%	250.16
50%	261.61
60%	274.83
70%	289.05
80%	304.94
90%	325.72

Exhaust gases were sampled with several instruments. NO_x, CO₂, CO, and light hydrocarbons were measured using an AVL FTIR supplied with lines heated to 191 °C. Soot concentrations were measured with an AVL Microsoot photoacoustic analyzer. Particle distributions were measured using a TSI scanning mobility particle sizer (SMPS). Total hydrocarbons were measured with a Combustion fast flame ionization detection system supplied by a line heated to 191 °C.

To simulate PM formation in atmospheric dilution conditions, controlled exhaust dilution was a necessity. A dilution system was constructed based on a design by Kittelson and Khalek, [10] as shown in Figure 1. This two-stage dilution system uses vacuum ejectors to pull exhaust gas through an orifice at a dilution ratio of approximately 12:1. The exhaust was sampled at a port on the 2.5" diameter exhaust pipe at a location 8 feet downstream of the exhaust manifold to most closely replicate conditions on a vehicle tailpipe. The primary ejector was supplied with clean, temperature controlled CO₂ and H₂O-free compressed air which was cooled with a reservoir of dry ice. The temperature of the compressed air supply was controlled such that the mixture of the compressed air and raw exhaust reach the target dilution temperature after adiabatic mixing. The resulting aerosol was aged in a dilution tunnel for approximately 1 second. The dilution ratio was monitored continually by measuring the CO₂ concentration within the aging tunnel using a medical grade CO₂ instrument.

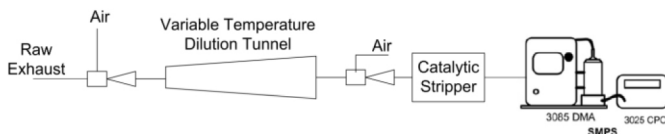


Figure 1. PM sampling system

A catalytic stripper effective at removing HC and sulfate material was used to remove volatile organic material and sulfates from the exhaust PM, leaving only solid PM material. The device consists of a heated oxidation catalyst through which the diluted sample passed. PM resulting from processing in the catalytic stripper has been shown to be primarily soot and ash [11].

Total PM mass was calculated by integrating the particle volume distribution as measured by SMPS. For volatile PM, this method can prove more effective than filtration for mass measurement, as evaporation of volatile material from filters can cause negative filtration artifacts [12]. Exhaust processed with the catalytic stripper to identify solid PM was calculated in the same manner. Particles are assumed to be spherical and to have a specific gravity of 1 for conversion from volume to mass.

To identify differences in PM composition based on particle size, a tandem dynamic mobility analyzer (TDMA) system with thermal conditioning was developed (Figure 2) based on a design used by Sakurai [13]. This device allows selection of a near-monodisperse aerosol sample by selecting particles of similar electro-mobility. After selecting the monodisperse PM, the thermal conditioning section processed the aerosol under controlled temperature conditions, causing a change in particle size due to evaporation of volatile PM species. The resulting change in particle size was measured using the SMPS. TDMA allowed characterization of PM volatility at specific particle sizes, making it an effective technique for measuring size-dependent PM characteristics. If a monodisperse aerosol is thermally conditioned, and the result is a multi-modal particle distribution caused by different rates of shrinkage, then

particles at that size are described as externally mixed in a study by Sakurai[14]. In a study using TDMA with thermal conditioning, Sakurai discovered that 70nm diesel CC PM was comprised of two particle types: "more volatile" and "less volatile", as two distinct modes resulted from the original 70nm selection. By selecting multiple particle sizes for thermal conditioning, size dependent mixing characteristics of diesel PM can be investigated.

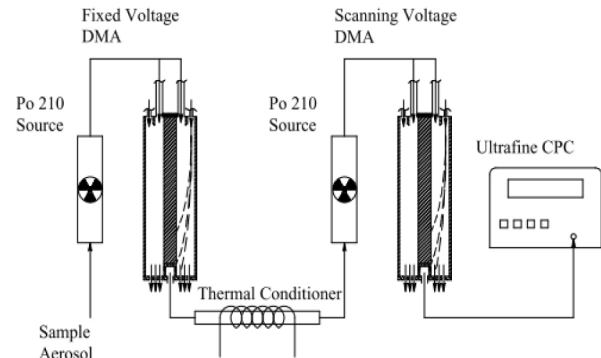


Figure 2. TDMA with Thermal Conditioner

Experimental Strategy

Each of the four combustion modes in this study were run on separate days. Before beginning data acquisition, the engine was operated at the prescribed combustion condition for several hours to verify the steady operating conditions necessary for testing. Two LTC combustion strategies were implemented in this study. Early injection timing 1500 RPM LTC (ELTC) at 2 Bar BMEP, and late injection timing 1500 RPM LTC (LLTC) at 4 Bar BMEP similar to those described in Ref.[8] were tested alongside CC conditions at equivalent speeds and loads. The operating settings are defined in Table 3.

Table 3. Engine Operating Parameters

Combustion Type	2 Bar Conventional	2 Bar ELTC	4 Bar Conventional	4 Bar LLTC
Load (N•M)	32.9	33.7	66.1	67.7
Speed (RPM)	1498	1498	1498	1498
Injection Pressure (Bar)	500	800	750	1200
Main Inj. Timing (DBTDC)	7	20	10	3
Main Inj. Duration (μs)	0.613	0.513	0.632	0.508
Pilot Inj. Timing (DBTDC)	19	N/A	21	N/A
Pilot Inj. Duration (μs)	0.21	N/A	0.1	N/A
EGR rate (%)	32.9	59.8	23.5	39
Intake Charge Temp (°C)	62.2	63.7	56.7	59.9
BSFC (g/kW•hr)	293.2	315.9	242.7	257.2
Air-Fuel ratio	41.50:1	23.44:1	27.31:1	18.11:1
Swirl Angle (deg.)	28.1	23.1	35.7	37.2