

Effects of Aftertreatment on 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 effectively limits soot and oxides of nitrogen (NO_x) emissions in-cylinder. Unfortunately, LTC results in increased hydrocarbon emissions as compared to conventional diesel combustion (CDC). Previous work has shown that exhaust conditions resulting from LTC inhibit oxidation of HC within a diesel oxidation catalyst (DOC). Further, these elevated HC emissions result in engine-out particulate matter (PM) that primarily consists of semi-volatile organic material. The current work shows that a DOC incompletely oxidizes this PM forming material. These results investigated the effectiveness of both a DOC and a diesel particulate filter (DPF) in reducing particle emissions for LTC. In this work, engine-out, DOC-out, and DPF-out exhaust were sampled using a micro-dilution system. Particle distributions were determined with a scanning mobility particle sizer (SMPS) and engine exhaust particle sizer (EEPS). A catalytic stripper (CS) was used to differentiate volatile and solid material in the PM. A Fourier Transform Infrared (FTIR) analyzer was used for light HC speciation. Soot concentrations were determined using a photo-acoustic sensor (Microsoot). The study revealed that a DOC is only partially effective at eliminating PM from LTC exhaust, with a DPF reducing LTC particle emissions further, despite the particle volatility. However, the results show that as aftertreatment HC loading increases, the storage ability is compromised, and its PM removal efficiency is lessened. This suggests that a DOC-DPF aftertreatment system can effectively remove PM from LTC exhaust as long as DPF regeneration occurs during the operating cycle.

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INTRODUCTION

The internal combustion engine has economy, power, reliability, and efficiency characteristics that have made it the primary source of transport power in modern society. Threats of climate change, the rising cost of fuel, and aggressively implemented federal fuel economy standards have continued to force fuel economy improvements from manufacturers, and motivate research in alternative combustion modes. Low temperature combustion (LTC) modes such as premixed charge compression ignition (PCCI), reactivity controlled compression ignition (RCCI), and homogeneous charge compression ignition (HCCI) have shown potential for improving fuel economy and reducing emissions as compared to conventional mixing controlled diesel combustion (CDC) [1]. Diesel-fueled LTC strategies are typically implemented at low engine load and speed and extensive work has been done to characterize combustion in this region [2,3,4]. Due to its limited load range, LTC must be used in engines with aftertreatment systems designed for CDC at higher engine speed and load. Therefore, these aftertreatment systems must be capable of reducing emissions from both LTC and CDC operation. While aftertreatment performance and operation has been extensively characterized for CDC, its effectiveness for LTC is still not completely understood.

A study on DOC performance for LTC exhaust has shown that the high HC and CO levels deactivate a DOC and result in reduced conversion of these species. Further, the sub 200 °C exhaust temperatures present for low load LTC may be insufficient for catalyst activation [5]. This can result in unacceptable PM emissions downstream of the DOC [6] due to gas to particle conversion in the primary exhaust plume. Further, the low volatility species which tend to form PM in LTC are of higher molecular weight than most hydrocarbon emissions, and face a greater diffusion barrier to reaching a DOC surface and oxidizing [7]. This phenomenon is also supported by the work of Bohac et al. [8] which showed that DOC HC conversion efficiency decreases with increasing carbon number. This raises additional concerns that particle forming HC may escape the aftertreatment system and form particles upon dilution in the atmosphere.

DPFs are known to be highly effective for removal of PM from CDC [9] in diesel engines, with efficiencies greater than 90% over a large range of particle size. Further, their removal efficiency for sub 100nm particles increases with increasing DPF loading, as the accumulating soot cake provides an additional filtration mechanism [10]. Because PM from LTC is comprised of only a fraction of the soot of CDC, temporal improvements in DPF efficiency due to the soot cake layer may not have the same effect.

The objective of this study is the determination of the effects of aftertreatment on semi-volatile PM emitted from a low-load LTC combustion mode in a light-duty diesel engine. It is known that the conditions present in LTC exhaust are detrimental to HC conversion in aftertreatment, however, the impact of this effect on DPF-out PM formed upon dilution in atmosphere demands further attention. Characterizing these effects is important for the development and application of engine mapping, and regeneration strategies used while operating in combustion modes that emit volatile PM. These include modes such as LTC, idle, and active DPF regeneration modes using post-injection.

EXPERIMENTAL

Engine Setup

Ultra low sulfur diesel #2 (ULSD) was used for the duration of the study, with properties listed in Table 1. This study was conducted using a modern General Motors 2.0 liter direct injection turbodiesel engine with the specifications listed in Table 2. This engine is equipped with variable geometry turbocharging, variable swirl actuation, and electronic EGR control. The engine was controlled using a National Instruments configurable engine control unit with data acquisition. The engine was modified for laboratory duty with an intake manifold temperature control system and an EGR cooler modified for higher loads. The engine was fitted with a close-coupled factory DOC-DPF aftertreatment system modified for laboratory study. Further details of the engine setup can be found in Lucachick et al. [11].

Table 1. 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
Cetane Number	41.1
Carbon (Wt%)	86.99
Hydrogen (Wt%)	13.01
Oxygen (Wt%)	<.05%
Sulfur (Wt%)	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

Table 2. Engine specifications

Number of Cylinders	4
Displacement (cc)	1956
Bore (mm)	83.0
Stroke (mm)	90.4
Compression Ratio	16.5
Output @ engine speed KW/RPM	117.3/4000
Torque @ engine speed N·M/RPM	259/1750
Bosch Solenoid Injector Hole Quantity	7

Gaseous emissions were measured with an AVL FTIR through sample lines heated to 191 °C. The sampling probe was switched between engine-out, DPF-out, and intake-out locations during the course of the experiments. HC emissions were calculated (Equation 1) by summing the HC species measureable by the FTIR using an approximation by Fang et al. [12]. Soot concentrations were measured using an AVL Microsoot photoacoustic analyzer.

$$HC_{ppm} = x_{CH_4} + 2 \cdot x_{C_2H_2} + 2 \cdot x_{C_2H_4} + 3 \cdot x_{C_3H_6} + 3 \cdot x_{C_3H_8} + 4 \cdot x_{C_4H_6} + 4 \cdot x_{C_4H_8} + 7.5 \cdot AHC \quad (1)$$

Dilution in the atmosphere is an important event in the formation of exhaust particles. Particles from LTC exhaust are especially sensitive to dilution conditions because of their high volatility [11]. To carefully control and monitor dilution conditions, a micro-dilution system (Figure 1) modeled after a design by Kittelson and Khalek [13], was used to sample and dilute exhaust PM under controlled temperature and flow conditions. The dilution temperature was maintained at 25 °C for all particle sampling.

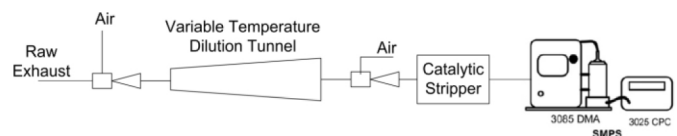


Figure 1. PM sampling system

Exhaust particles for both CDC and LTC were sampled downstream of the turbocharger. Though DPF removal efficiency for CDC particles is known to increase with soot loading[10], the temporal removal efficiency effects for LTC particles is not known. Thus, LTC particles are sampled at DOC-out, and DPF-out locations in addition to downstream of the turbocharger. All particle distributions were measured using SMPS, after dilution with clean, dry, CO₂ free air. For all particle measurements, the CO₂ concentration after dilution was monitored to determine the dilution ratio. For DPF-out LTC particles, an engine exhaust particle sizer (EEPS) was utilized to observe transient phenomenon, and particle distributions were measured at a rate of 1 Hz for the entirety of the test.