

Emission Characteristics of a Diesel Engine Operating with In-Cylinder Gasoline and Diesel Fuel Blending

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ABSTRACT

Advanced combustion regimes such as homogeneous charge compression ignition (HCCI) and premixed charge compression ignition (PCCI) offer benefits of reduced nitrogen oxides (NO_x) and particulate matter (PM) emissions. However, these combustion strategies often generate higher carbon monoxide (CO) and hydrocarbon (HC) emissions. In addition, aldehydes and ketone emissions can increase in these modes. In this study, the engine-out emissions of a compression-ignition engine operating in a fuel reactivity-controlled PCCI combustion mode using in-cylinder blending of gasoline and diesel fuel have been characterized. The work was performed on a 1.9-liter, 4-cylinder diesel engine outfitted with a port fuel injection system to deliver gasoline to the engine. The engine was operated at 2300 rpm and 4.2 bar brake mean effective pressure (BMEP) with the ratio of gasoline to diesel fuel that gave the highest engine efficiency and lowest emissions. Engine-out emissions for aldehydes, ketones and PM were compared with emissions from conventional diesel combustion. Sampling and analysis was carried out following micro-tunnel dilution of the exhaust. Particle geometric mean diameter, number-size distribution, and total number concentration were measured by a scanning mobility particle sizer (SMPS). For the particle mass measurements, samples were collected on Teflon-coated quartz-fiber filters and analyzed gravimetrically. Gaseous aldehydes and ketones were sampled using dinitrophenylhydrazine-coated solid phase extraction cartridges and the extracts were analyzed by liquid chromatography/mass spectrometry (LC/MS). In addition, emissions after a diesel oxidation catalyst (DOC) were also measured to investigate the destruction of CO, HC and formaldehydes by the catalyst.

INTRODUCTION

In recent years, much emphasis has been placed on utilization of lean burn engines in the transportation sector for their higher fuel efficiency and lower greenhouse gas emissions. Lean burn engines, however, produce high levels of nitrogen oxides (NO_x) and particulate matter (PM) emissions. These emissions must be reduced to regulatory levels set by the U.S. Environmental Protection Agency (EPA) in order to realize the advantages of lean burn engines in production vehicles. Removal of NO_x from lean exhaust is particularly challenging because the excess oxygen prevents use of the three-way catalyst technology that has become the standard for controlling NO_x emissions from stoichiometric engines.

Advancements in both combustion strategies and emissions control technologies have been made in recent years to meet current and future stringent exhaust emissions standards. Current production diesel vehicles in the U.S. are equipped with a diesel particulate filter (DPF) for treating PM emissions and a lean NO_x trap (LNT) or a selective catalytic reduction catalyst (SCR) to control NO_x emissions. Lowering engine-out NO_x and PM emissions would reduce some of the burden from these aftertreatment devices. Specifically, lower PM emissions can result in less frequent DPF regenerations and reduced fuel penalty associated with them. Similarly, lower NO_x emissions may reduce the performance, cost and size requirements of NO_x control devices. In conventional diesel combustion, reduction of one pollutant is typically achieved at the expense of the other. For example, increasing exhaust gas recirculation (EGR) decreases engine-out NO_x emissions but increases PM emissions.

Advanced combustion regimes are being investigated as means for simultaneous reduction of engine-out NO_x and PM

emissions. Most advanced combustion strategies can be categorized as low temperature premixed combustion. These strategies use high EGR rates to reduce the flame temperature, thus, lowering NO_x formation, and advanced timing to create a near homogeneous charge prior to the start of combustion which inhibits soot formation. Examples of such strategies are homogenous charge compression ignition (HCCI) and premixed charge compression ignition (PCCI) combustion. It has been shown that HCCI and PCCI can simultaneously reduce NO_x and PM emissions while maintaining or improving thermal efficiency [1, 2, 3, 4]. However, these strategies are most often limited to low-load operating conditions due to high-pressure rise rates associated with premixed combustion [5, 6].

Recent theoretical and experimental studies describe a combustion regime that uses a combination of gasoline and diesel fuels to control PCCI combustion by effectively controlling fuel reactivity in the combustion cylinder [5, 6]. This reactivity-controlled compression ignition (RCCI) combustion may be extended to a wider engine operating range by adjusting different ratios of fuel blends. Most of the experimental work using dual-fuel RCCI combustion has been performed on a single-cylinder engine. Curran et al. [7] extended the dual-fuel RCCI modeling and single-cylinder experiments of Kokjon et al. [6] to a multi-cylinder light-duty diesel engine. In their study, the performance and emissions of a 4-cylinder diesel engine operating at 2300 rpm and 4.2 bar brake mean effective pressure (BMEP) with dual-fuel RCCI combustion were evaluated. The challenges of running a multi-cylinder engine in dual-fuel RCCI such as the behavior of turbo-machinery and the natural cylinder-to-cylinder imbalances were also addressed [7].

Advanced combustion regimes such as HCCI and PCCI often generate higher carbon monoxide (CO) and hydrocarbon (HC) emissions than conventional combustion. In addition, aldehydes and ketone emissions can increase in these modes [8]. As a complimentary study to the foundation work of Curran et al. [7], the present investigation provides extensive engine-out emissions speciation of a multi-cylinder engine operating in the RCCI regime with in-cylinder blending of gasoline and diesel fuel. Engine-out emissions data for several mobile source air toxics (MSATs) including formaldehyde, acetaldehyde, benzene, PM are presented and compared with emissions from conventional diesel combustion and PCCI combustion using diesel fuel only. Furthermore, the emissions treated by a diesel oxidation catalyst (DOC) are also presented to assess the destruction of CO, HC and formaldehydes by the catalyst for different combustion modes.

EXPERIMENTAL METHODS

Engine-out gaseous and particle emissions were sampled from the exhaust of a multi-cylinder diesel engine operating

in a dual-fuel RCCI combustion regime, and the results of the analysis were compared with emissions from conventional diesel combustion and diesel PCCI combustion. In addition, the engine was equipped with a DOC to assess the effectiveness of the catalyst in removing HC, CO and formaldehydes from the exhaust.

ENGINE PLATFORM

This work was conducted on a modified 1.9-liter four-cylinder General Motors (GM) common rail diesel engine coupled to a motoring direct current (DC) dynamometer. The engine was equipped with a Bosch common rail fuel injection system, a variable geometry turbocharger (VGT), an electronic EGR valve, and a swirl actuator. The specifications for the engine are shown in [Table 1](#).

The intake manifold was outfitted with four extended tip narrow spray angle Multec® 3.5 port fuel injection (PFI) gasoline injectors from Delphi Automotive Systems to deliver gasoline directly into the non-swirl actuated intake port of the engine. The gasoline supply pressure for gasoline injectors was 380 kPa (55 psi). More specifics on a PFI system can be found in another publication [7].

A custom full-pass Driven engine control system was utilized for all of the engine controls. This control system enables precise control of many of the engine control parameters. During normal engine operation, the stock engine calibration was employed; however, a number of engine parameters were modified when the engine was operated in diesel PCCI and dual-fuel RCCI such as fuel injection pressure, EGR, swirl, boost, injection pulse width, timing and number of injection events for each direct injection (DI) diesel injector and PFI gasoline injector.

All data reported in this work was taken with the engine operating at 2300 rpm and 4.2 bar BMEP. The engine operating parameters for dual-fuel RCCI combustion were chosen such that highest engine efficiency and lowest possible engine-out emissions were obtained, and they were based on the study conducted by Curran et al. [7]. For diesel PCCI combustion, the engine parameters were modified to achieve at least 50% reduction in engine-out NO_x and PM emissions while maintaining thermal efficiency of conventional diesel combustion. [Table 2](#) lists key parameters used in the conventional diesel, diesel PCCI and dual-fuel RCCI combustion.

The exhaust aftertreatment system consisted of a diesel oxidation catalyst. The DOC was a model catalyst with 100 g/ft³ Pt and had a volume of 1.25 liters. A diagram with details of the test system is shown in [Figure 1](#).

Table 1. Engine specifications

Engine Type	GM direct injection diesel engine
Number of cylinders	4
Displacement	1.9-liter
Bore x stroke	82.0 x 90.4 mm
Compression ratio	17.5
Piston Geometry	Bowl-in-Piston
Number of valves per cylinder	4
Injection System	Common Rail
Injector Location	Centrally Mounted
Rated Power	110 kW at 4000 rpm
Rated Torque	315 Nm at 2000 rpm

Table 2. Operating Conditions for the 2300 rpm 4.2 bar BMEP

	Conventional Diesel	Diesel PCCI	Dual-Fuel RCCI
Intake Air Flow (kg/hr)	99.81	89.35	117.52
EGR (%)	29.4	40.0	0
Diesel Flow (g/s)	1.17	1.19	0.29
Gasoline Flow (g/s)	0	0	0.87
Percent Gasoline (%)	0	0	74.8
Main Start of Injection (°BTDC)	1.7	4.7	60
Pilot Start of Injection (°BTDC)	27.5	-	-
Fuel Rail Pressure (bar)	1026	1227	500
Intake Pressure (bar)	1.20	1.20	1.22
Swirl Duty Cycle (%)	53.3	53.3	80.0
Intake Temperature (°C)	93.4	116.2	40.2
Exhaust Temperature (°C)	413.6	418.7	248.8

FUEL

Experiments were carried out using 2007 certification ultra-low sulfur diesel (ULSD) and unleaded test gasoline (UTG) 96. Tables 3 and 4 show selected fuel properties provided by the vendor for the ULSD and UTG 96, respectively.