

Effectiveness of Diesel Oxidation Catalyst in Reducing HC and CO Emissions from Reactivity Controlled Compression Ignition

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ABSTRACT

Reactivity Controlled Compression Ignition (RCCI) has demonstrated diesel-like or better brake thermal efficiency with significant reductions in nitrogen oxide (NO_x) and particulate matter (PM) emissions. Hydrocarbon (HC) and carbon monoxide (CO) emission levels, on the other hand, are higher and similar to those of port fuel injected (PFI) gasoline engines. The higher HC and CO emissions combined with the lower exhaust temperatures during RCCI operation present a challenge for current exhaust aftertreatment technologies. The reduction of HC and CO emissions in a lean environment is typically achieved with an oxidation catalyst. In this work, several diesel oxidation catalysts (DOC) with different precious metal loadings were evaluated for effectiveness to control HC and CO emissions from RCCI combustion in a light-duty multi-cylinder engine operating on gasoline and diesel fuels. Each catalyst was evaluated under steady-state engine operation with temperatures ranging from 160 to 260°C. A shift to a higher light-off temperature was observed during the RCCI operation. In addition to the steady-state experiments, the performance of the DOCs were evaluated during multi-mode engine operation by switching from diesel-like combustion at higher exhaust temperature and low HC/CO emissions to RCCI combustion at lower temperature and higher HC/CO emissions. High CO and HC emissions from RCCI generated an exotherm temporary keeping the catalyst above the light-off temperature.

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INTRODUCTION

Reactivity controlled compression ignition is a dual-fuel advanced combustion strategy that uses two fuels of different reactivities to tailor the fuel mixture to a particular engine speed and load [1,2,3,4,5]. This low temperature combustion (LTC) strategy has been shown to provide additional control over the combustion process as compared to single-fuel advanced combustion strategies. Namely, the global fuel reactivity allows control over combustion phasing, and a fuel reactivity gradient allows for control over maximum cylinder pressure rise rate (MPRR).

RCCI has been developed and demonstrated on a light-duty multi-cylinder diesel engine with in-cylinder blending of gasoline and diesel fuels as well as alternative fuels [6,7,8,9,10,11,12]. RCCI combustion demonstrated diesel-like or better brake thermal efficiency with significant reductions in particulate matter (PM) and nitrogen oxides (NO_x) emissions. RCCI covers a wider range of the engine speed/load map in comparison to other LTC strategies due to

the manipulation of the combustion process enabled through the dual-fuel approach.

A major challenge of RCCI operation is that HC and CO emission levels are similar to those of gasoline engines but occur at much lower exhaust temperatures thereby making oxidation by catalysis difficult [13,14,15]. The lower exhaust temperatures are due to the high efficiency associated with the low temperature combustion process.

The reduction of HC and CO emissions will require the use of oxidation catalysts. Several diesel oxidation catalysts (DOC) were investigated in this study. While exhaust temperatures are lower than observed for convention diesel combustion, the DOC technology is the closest potential solution available. Diesel oxidation catalysts make use of catalysts containing precious metals such as platinum (Pt) and palladium (Pd) for treating CO/HC emissions. The loading and ratio of these two metals are optimized for a specific application in terms of durability, performance and cost.

In this study, the performance of two commercially available DOCs with different precious metal loadings and Pt:Pd ratios were characterized and compared to a model



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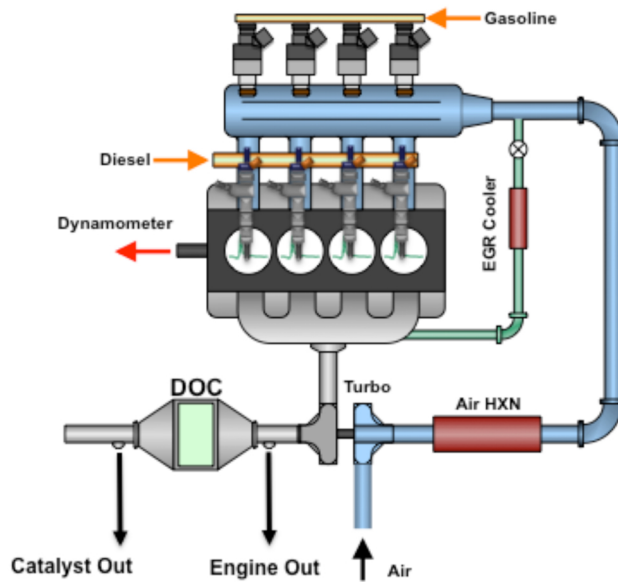


Figure 1. ORNL Multi-Cylinder RCCI Engine

DOC containing Pt only. Each catalyst was evaluated for CO/HC oxidation activity and light-off temperatures with RCCI exhaust containing both unburned and partially burned hydrocarbons from both fuels.

EXPERIMENTAL SETUP

Engine Platform

The engine used for this study is a modified 2007 General Motors 4-cylinder 1.9L direct-injection turbocharged diesel engine. The base engine has a rated power of 110 kW and a rated torque of 315 Nm. The original equipment manufacturer (OEM) pistons were replaced with open bowl pistons modified for RCCI engine operation. The modified piston bowl geometry was designed using CFD modeling. The piston design is based on a heavy-duty piston to lower the surface area of the piston in order to minimize heat transfer losses, which also results in a reduced compression ratio from 17:1 in the OEM configuration to 15:1. The lower compression ratio allows higher load RCCI operation while maintaining reasonable pressure rise rate limits. The modified piston still allows for conventional diesel combustion (CDC) operation; however, the injection strategy and swirl ratio must be adjusted to match combustion conditions of CDC operation with the OEM piston. More information on the piston design can be found in the paper by Hanson et al. [23]. The diesel injection system and variable geometry turbo charger (VGT) were left in production form. The intake manifold, however, was modified to incorporate extended tip narrow spray angle PFI injectors for the gasoline supply. A more in-depth discussion of the intake manifold modifications can be found in Curran et al. [20]. [Figure 1](#) shows the overall fuel system layout for RCCI operation. [Table 1](#) shows engine specifications for the base engine.

[Tables 2](#) and [3](#) show the injector specifications for the DI and PFI injectors, respectively.

The stock ECU was replaced with a full-pass DRIVEN control system which allowed simultaneous control of the PFI and DI fuel systems and all other engine parameters. Engine torque was measured using an absorbing eddy-current dynamometer. The DI fuel flow rate was measured with a Micro Motion Coriolis fuel meter, while the PFI fuel flow rate was measured using a Max Machinery 710-213 positive displacement volumetric flow measurement system. The intake air flow rate was measured using a laminar flow element and the stock intake mass-airflow sensor. Conditioned air was supplied to the engine at a constant temperature of 25°C and a relative humidity of 58%.

High speed combustion data was acquired using Kistler model 6058A pressure sensors installed in the glow plug ports of all 4 cylinders. Individual Kistler type 5010 Dual-Mode Amplifiers were used to process the pressure signals, and the built in combustion package from Driven was used to process the data. Combustion metrics were monitored and recorded using the DRIVEN combustion analysis toolkit (DCAT). All brake thermal efficiencies presented here are calculated using the lower heating value (LHV) of the fuels used and brake power as measured from the dynamometer.

Table 1. GM 1.9 L RCCI Configuration

Number of Cylinders	4
Bore (mm)	82.0
Stroke (mm)	90.4
Compression Ratio	15.1

Table 2. Diesel injector specifications

Number of Nozzle Holes	7
Included Spray Angle (°)	148

Table 3. Port-fuel injector specifications

Number of Nozzle Holes	4
Cone Angle (°)	15
Separation Angle (°)	22

Fuel

The DI fuel used in this study was a 2007 certification grade Ultra Low Sulfur Diesel (ULSD) fuel with a cetane number (CN) of 42.5. The base gasoline was UTG 96 with an antiknock index (AKI) of 92.1 containing no ethanol. Key fuel specifications for both fuels are shown in Table 4.

Table 4. Fuel specification for UTG-96 and ULSD

Specification	UTG-96	ULSD
Lower Heating Value (kJ/kg)	43124	42879
Specific Gravity	0.7389	0.848
H (weight %)	13.9	13.2
C (weight %)	86.1	86.8
Oxygen (weight %)	0.0	0.0
Aromatics (weight %)	32.7	29.9
Initial Boiling Point (°C)	34	184
Final Boiling Point (°C)	185	332
Research Octane Number (RON)	96.1	NA
Motor Octane Number (MON)	88.2	NA
Anti-Knock Index (AKI)	92.1	NA
Cetane Number	NA	42.5

Emission Sampling

Raw exhaust was sampled at the engine-out and catalyst-out locations using standard analysis techniques. A California Analytical Instruments (CAI) heated flame ionization detector (FID) was used to measure total unburned hydrocarbons. A CAI chemiluminescence (CLD) instrument was used to measure NO_x. CO and CO₂ were measured using CAI non-dispersive infrared (NDIR) instruments. Intake and exhaust O₂ were measured using CAI paramagnetic detector (PMD) analyzers. Both intake and exhaust CO₂ were measured to determine the EGR rate. Sampled emissions were chilled prior to measurement for PMD and NDIR instruments. Both intake and exhaust sample streams were conveyed from heated filters to the instruments through heated lines maintained at 190°C. PM emissions were roughly monitored by measuring the filter smoke number (FSN) using an AVL model 415 smoke meter.

In addition to standard emissions benches, raw exhaust at the engine-out and catalyst-out locations was also sampled

with a MKS MultiGas Model 2030 HS Analyzer. The MultiGas is a Fourier-Transform Infrared (FTIR) spectroscopy-based gas analyzer with a heated 5.11 m multi-pass gas cell capable of measuring multiple gases. The species of principal interest were CO, CO₂, nitrogen monoxide (NO), and nitrogen dioxide (NO₂). The sample was routed through a heated filter for the removal of particulates prior to the FTIR analysis.

Catalysts

Two commercially available DOCs and one model DOC were evaluated in the study. DOCs A and B were removed from the exhaust system of a Model Year (MY) 2011 Ford Diesel Super Duty pick-up truck. The MY 2011 Ford exhaust system consisted of two DOCs in tandem. DOC A came from the front section (engine side) of the Ford exhaust system, and DOC B came from the back. A sample from a center of the front face of each DOC was sent to Galbraith Laboratories for analysis. Duplicate 60 element semi-quantitative metal screens were performed on each sample. A variation of up to 20% in precious metal loading was observed in the duplicates with averages shown in Table 5. The model DOC, supplied by EmeraChem, is a 300 cells/in² cordierite substrate coated with a 100 g/ft³ Pt on a 160 m²/g γ-Al₂O₃ catalyst.

Table 5. DOC details

	DOC A	DOC B	Model DOC
Cell Density, csi	400	400	300
Pt loading, g/ft ³	71	53	100
Pd loading, g/ft ³	23	21	0
Pt:Pd ratio	3:1	2.5:1	1:0

Each catalyst was degreased for 3 hours in the engine exhaust at 730°C. The elevated temperatures for degreasing were obtained via in-cylinder fuel enrichment typically used in DPF regenerations.

EXPERIMENTS

DOC effectiveness in controlling HC and CO emissions was investigated over four steady-state engine speed and load conditions under both CDC and RCCI operation. The four steady-state points are shown in Table 6.

Table 6. Steady-state operating points

	Speed, rpm	BMEP, bar
1.	1250	2.0
2.	1250	5.0
3.	2000	2.0
4.	2000	6.0

In addition to the steady-state experiments, the performance of the DOCs were evaluated during multi-mode engine operation by switching from CDC at higher exhaust