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Optimization of performance and operational cost for a dual mode diesel-natural gas RCCI and diesel combustion engine

Ehsan Ansari*, Mahdi Shahbakhti, Jeffrey Naber

Mechanical Engineering – Engineering Mechanics, Michigan Technological University, 1400 Townsend Dr., Houghton, MI 49931, USA

HIGHLIGHTS

- RCCI has better performance and lower operational cost in comparison to CDC mode.
- At medium and high loads, RCCI showed better fuel economy, lower NOx and PM emissions.
- The optimum EGT range for dual mode RCCI-CDC operation is around 400 to 425 °C.
- In optimum calibration, the CA50 retards as engine load increases.
- RCCI engines are useful in on-road applications and stationary applications.

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ABSTRACT

Diesel-NG fuel blends are increasingly being used in Reactivity Controlled Compression Ignition (RCCI) internal combustion engines due to high Brake Thermal Efficiency (BTE), low NOx and PM emissions. It also has few disadvantages such as high unburned Hydro Carbon (HC) and Carbon Monoxide (CO) emissions and relatively low Exhaust Gas Temperature (EGT). This study determines the optimum combustion mode between RCCI and Conventional Diesel Combustion (CDC) at different loads while meeting the Environmental Protection Agency (EPA) emission regulation. A Cost Function (CF) including Brake Specific Fuel Consumption (BSFC) and Brake Specific Urea Consumption (BSUC) is considered and minimized in this study. The optimization of input variables is done between 3 and 12 bar Indicated Mean Effective Pressure (IMEP) engine load. The study aims to calibrate the dual fuel diesel/NG RCCI engine to meet Tier 3 Bin 20 EPA standard, with or without after-treatment system, while minimizing the cost of operation.

New parametric empirical models are developed and validated using experimental data from a light duty 1.9L inline 4 cylinder Compression Ignition (CI) engine as a function of independent input variables. All the experiments were conducted at Advanced Power System (APS) facility at Michigan Technological University. These models predict HC, CO, PM and NOx emissions, EGT and BSFC. These models are then used to predict new operating points to increase the population in the optimization process. The computed EGT is used to estimate the Selective Catalyst Reduction (SCR) and Diesel Oxidation Catalyst (DOC) efficiencies to assess the emission data with different input variables by considering the after-treatment system to see if they meet the tailpipe emission regulation. The optimization results recommend using Diesel/NG RCCI at 7 to 12 bar IMEP operating conditions and use CDC for below 7 bar IMEP operating condition.

1. Introduction

Natural Gas (NG) has been used as an alternative fuel for over 100 years [1]. Some of the recent applications include NG with diesel in dual fuel Low-Temperature Combustion (LTC) regimes [2–19]. Due to the high octane number of NG, it is possible to increase the compression ratio and increase the thermal efficiency via extending the load limit [2,20–22]. RCCI is an attractive dual fuel LTC combustion mode which has shown significant improvement in reducing NOx and PM emissions in comparison to single fuel diesel mode. Despite these advantages, RCCI has relatively high HC and CO emissions and low EGT which makes the reduction and oxidation process difficult for exhaust after-treatment systems. An optimization is needed to precisely select the RCCI input parameters (including injection strategy, injection pressure,

* Corresponding author.
E-mail address: eansari@mtu.edu (E. Ansari).

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Nomenclature

ACAP	advance combustion analysis program [–]
ANR	ammonia nitrogen ratio [–]
BSFC	brake specific fuel consumption [g/kW h]
BR	blending ratio [%]
BSUC	brake specific urea consumption [g/kW h]
BTDC	before top dead center [°CAD]
BTE	brake thermal efficiency [%]
CDC	conventional diesel combustion [–]
CF	cost function [–]
CFD	computational fluid dynamic [–]
CI	compression ignition [–]
CO	carbon monoxide [g/kW h]
COV	coefficient of variation [%]
CR	compression ratio [–]
DI	direct injection [–]
DOC	diesel oxidation catalyst [–]
DOE	design of experiment [–]
DPF	diesel particulate filter [–]
EGR	exhaust gas recirculation [%]
EGT	exhaust gas temperature [°C]
EHC	electrically heated catalyst [–]
EPA	environmental protection agency [–]
EVC	exhaust valve close [°CAD]
EVO	exhaust valve open [°CAD]
γ	isentropic coefficient [–]
HCCI	homogeneous charge compression ignition [–]
IMEP	indicated mean effective pressure [bar]
ISFC	indicated specific fuel consumption [g/kW h]
IVC	intake valve close [°CAD]
IVO	intake valve open [°CAD]
λ	lambda [–]
LHV	lower heating value [MJ/kg]
LTC	low-temperature combustion [–]
$\dot{m}_{Diesel}$	mass flow rate of diesel fuel [g/s]
$\dot{m}_{NG}$	mass flow rate of NG fuel [g/s]
MAP	manifold absolute pressure [kPa]
MPRR	maximum pressure rise rate [bar/deg]
NG	natural gas [–]
O_2	oxygen concentration [%]
NO_x	specific nitrogen oxides [g/kW h]
P	pressure [kPa]
PCCI	premixed charge compression ignition [–]
PFI	port fuel injection [–]
Q_{LHV}	lower heating value [MJ/kg]
RCCI	reactivity controlled compression ignition [–]
SCF	standard cubic feet
SCR	selective catalyst reduction [–]
SI	spark ignition [–]
SOI	start of injection [°CAD]
TDC	top dead center [–]
TDI	turbocharged direct injection [–]
V	volume [m^3]

boost and Exhaust Gas Recirculation - EGR) to maximize the engine BTE and minimize the tailpipe emissions to meet the U.S. Tier 3 Bin 20 emission regulation. Plenty of works are available in the literature for RCCI engines [3–10,23–37], but only a few works are found in the literature for optimization of RCCI combustion mode [9,27,32,34,38–41]. The summary of the prior optimization studies in RCCI combustion mode is provided in Table 1.

In recent studies [24,40], researchers from Universitat Politècnica de València, conducted an experimental study to investigate the capabilities of the diesel-gasoline RCCI for a single cylinder CI engine, that was modified for dual fuel operation. The optimized dual fuel injection strategy was changed as a function of engine load. It was observed that at low engine load operating conditions, early double diesel injections led to ultra-low PM and NOx emissions. At higher loads, early pilot diesel and close to TDC main injection strategy was performed. The diesel pilot injection increases the reactivity of the mixture in crevices and squish region, where low reactive fuel gets trapped and the main diesel injection acts as an ignition source. Due to the less mixing time, higher soot level was reported. Moreover, the partial diffusion burn rate provides precise control of combustion phasing, i.e., crank angle of 50% fuel burnt (CA50). At full load operating conditions, "Dual-Fuel Diffusion" (single delayed diesel injection) was used. Running the engine at

Table 1
RCCI optimization and parametric studies available in literature.

Target	Diesel-gasoline RCCI		Diesel-NG RCCI
Optimization study	Experiential	• RCCI/CDC – ethanol-gasoline/biodiesel – medium duty – Emissions regulation is considered [Benajes-2016] • Injection/Combustion strategy and piston bowl – Heavy Duty – Emission regulation is considered [Benajes-2017]	• DOE analysis and real-time optimization – Experimental – Light Duty – Emission regulation is NOT considered [Ansari-2016] • *This work – Injection pressure and timing, boost, EGR, EGT, EPA emission regulation and after-treatment is considered* *Experimental and Numerical*
	Numerical	• EGR, Equivalence Ratio – Heavy Duty – Emission regulation is NOT considered [Kavuri-2016] • Piston Bowl shape – Light Duty – Emission regulation is NOT considered [Hanson-2012] • Injection Strategy, BR, Spray Angle – Heavy Duty – Emission Regulation is considered [Nazemi-2015]	• BR, Injection Strategy, DI pressure, EGR – Numerical – Heavy Duty – Emission regulation is NOT considered [Nieman-2012]
Parametric study	Experiential	• Intake P, T and ∅ – Heavy Duty – Emission regulation is NOT considered [Splitter-2014] • Parametric study – Light Duty – Numerical – Emission regulation is NOT considered [Li-2014] • DI Injection timing sweep – Light Duty – Emission regulation is NOT considered [Walker-2013] • Transient study – Experimental – Light Duty - Emission regulation is NOT considered [Hanson-2014]	• Input variable sweep – Experimental – Heavy Duty – Emission regulation is NOT considered [Dahodwala-2014,2015] • DI injection timing sweep – Experimental – Heavy Duty – Emission regulation is NOT considered [Doosje-2014]
	Numerical	• EGR and PFI fuel – Heavy Duty – Emission regulation is considered [Yang-2013] • BR and SOI – Light Duty – Emission regulation is NOT considered [Li-2015]	• Initial Temperature, Fuel Composition – Heavy Duty – Emission regulation is NOT considered [Kakaee-2015]