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Fuel reactivity effects on the efficiency and operational window of dual-fuel compression ignition engines

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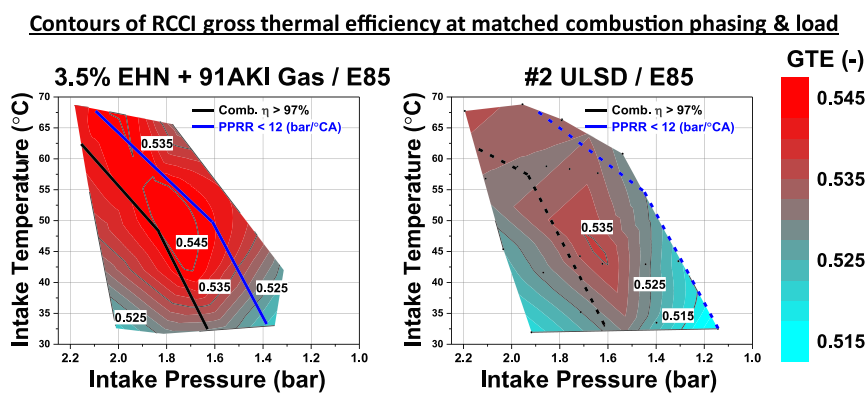
HIGHLIGHTS

- The study uses fixed load and TDC combustion phasing for a variety of intake conditions.
- Gross efficiency is maximized when the charge is approximately 2/3 premixed fuel 1/3 DI fuel.
- Engine conditions at optimal efficiency are affected by the difference in fuel reactivity.
- Fuel reactivity difference affects engine efficiency magnitudes, but not loss trend mechanisms.

GRAPHICAL ABSTRACT

Contours of RCCI gross thermal efficiency at matched combustion phasing and load



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ABSTRACT

An experimental engine efficiency study was conducted that explores the effects of direct injected fuel properties on gross thermal efficiency and operational authority as functions of intake pressure and temperature, and equivalence ratios (premixed and global) using the Reactivity Controlled Compression Ignition (RCCI) combustion strategy. The experiments were conducted in a heavy-duty single-cylinder engine at constant net IMEP of 8.45 bar, 1300 rev/min engine speed, with 0% EGR, and a CA50 combustion phasing of 0.5°CA ATDC. The engine was port fueled with E85 for the low reactivity fuel and direct injected with either #2 ULSD or 3% 2-ethylhexyl nitrate doped into 91 Anti-Knock Index (AKI) gasoline for the high reactivity fuel. The reactivity of the EHN enhanced fuel has been correlated to an AKI of approximately 56 and a cetane number of approximately 28. Intake pressure and temperature were swept independently of each other while combustion phasing and load were maintained by adjusting the global fuel reactivity and DI fuel timing as needed.

The results demonstrate that for fixed cycle thermodynamics, sources of engine inefficiency are functions of the premixed and global equivalence ratios. At extremes in either, excessive losses occur, decreasing the gross thermal efficiency. The study's findings demonstrate that losses can be minimized through proper balancing of the intake pressure and temperature, which are affected by fuel reactivity differences. Specifically, when the reactivity difference between the high and low reactivity fuel streams is reduced, with the EHN + Gas/E85 strategy, the control and effectiveness of the DI fuel is reduced, making combustion more abrupt. To reduce the peak pressure rise rate, leaner conditions were required, and the peak gross thermal efficiency increased. The results demonstrate that through proper optimization of both engine conditions, and fuels, increases in engine efficiency are possible with RCCI.

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Nomenclature

AHRR	Apparent Heat Release Rate
AKI	Anti-Knock Index
ASTM	American Society for Testing and Materials
ATDC	After Top Dead Center
BDC	Bottom Dead Center
CA	Crank Angle
CA50	Crank Angle at 50% Mass Fraction Burned
CDC	Conventional Diesel Combustion
CN	Cetane Number
CO	Carbon monoxide
DI	Direct Injection
DTBP	Di-tert-butyl Peroxide
E85	85% Ethanol and Gasoline by Volume
EGR	Exhaust Gas Recirculation
EHN	Ethylhexyl-Nitrate
EXH	Exhaust Loss
FID	Flame Ionization Detector
GTE	Gross thermal Efficiency
H/C	Hydrogen to Carbon ratio
HC	Hydrocarbon
HO_2	Hydroperoxy Radical
H_2O_2	Hydrogen Peroxide
HX	Heat Transfer Loss
IMEP	Indicated Mean Effective Pressure
$IMEP_g$	Gross Indicated Mean Effective Pressure
$IMEP_n$	Net Indicated Mean Effective Pressure
LHV	Lower Heating Value
LTC	Low Temperature Combustion
MON	Motor Octane Number
NO_x	Oxides of Nitrogen
NTC	Negative Temperature Coefficient
O_2	Oxygen
O/C	Oxygen to carbon ratio
OH	Hydroxyl Radical
PFI	Port Fuel Injection
PPRR	Peak Pressure Rise Rate
PRF	Primary Reference Fuels
$\dot{R}$	fuel radical
r_c	compression ratio
RCCI	Reactivity Controlled Compression Ignition
r/min	revolutions per minute
RON	Research Octane Number
SCOTE	Single Cylinder Oil Test Engine
SOI_1	Start of Injection One
SOI_2	Start of Injection Two
T	temperature
TDC	Top Dead Center
ULSD	Ultra Low Sulfur Diesel
η	efficiency
Φ	equivalence ratio
Φ_P	premixed equivalence ratio
Φ_G	global equivalence ratio

1. Introduction

Recent advances in high efficiency advanced combustion concepts have shown that high gross thermal efficiencies are achievable. For example, recent work with gasoline compression ignition by Sellnau et al. [1], Manente et al. [2], Ra et al. [3], and Hanson et al. [4] have demonstrated that gasoline compression ignition can be optimized to offer high thermal efficiencies. These strategies demonstrate methods for increasing engine efficiency through the use of gasoline fuels with diesel-like engine designs and technologies. Likewise, Southwest Research Institute has demonstrated that the conventional gasoline SI engine can exhibit increases in efficiency through the inclusion technologies like cooled external EGR [5], a technology traditionally used only in diesel and advanced combustion engines. These brief examples demonstrate how diesel and gasoline engines are evolving to be more similar in the quest for high efficiency.

A related strategy to the cited works is Reactivity Controlled Compression Ignition (RCCI). RCCI is an autoignition combustion strategy that operates through in-cylinder blending of diesel-like and gasoline-like fuels. The ratio and injection schedule of the fuels can be adjusted such that definable fuel reactivity gradients initiate and control ignition, as shown optically by Kokjohn et al. [6] and Splitter et al. [7]. By tailoring the ratios of the fuels as a function of the operating condition, direct control of pressure rise rate is possible, allowing combustion to be phased to near thermodynamically ideal conditions over wide speed and load ranges [8]. Recent multi-cylinder work by Curran et al. [9] has demonstrated that brake thermal efficiencies of RCCI are competitive or higher than production conventional diesel combustion, while achieving extremely low engine out emissions (without the need for NO_x and soot after treatment). Additionally, Splitter et al. [10] demonstrated that 1800 r/min full-load RCCI was possible with gasoline and diesel fuel in a single-cylinder heavy-duty engine with a compression ratio of 12 (20 bar BMEP). The cited RCCI studies have pointed to indirectly calculated reductions in heat transfer being present with RCCI. Recently, Hendricks et al. [11] demonstrated that approximately (25-50%) less piston heat transfer is present in RCCI as compared to conventional diesel combustion over a wide range of loads and speeds through direct in-situ fast response thermocouple piston surface heat flux measurement. Although these studies have demonstrated the operable flexibility and performance of RCCI, they have not investigated the relations between operational parameters that affect engine efficiency in detail.

To analyze engine efficiency, a first and second law approach can be used. That is, the energy or exergy (availability) flows/paths can be tracked. First and foremost, the source of exergy is from the fuel itself. Fuel exergy depends on its chemical composition, but for most fuels, it is roughly equal to the heating value of the fuel, a widely adopted approximation. Thus, the fuel path should be tracked to examine engine efficiency and the sources of losses. Several internal combustion engine exergy studies have been performed; with notable works by Caton on the availability destroyed in combustion [12] and during heat transfer [13]. In these works it was shown that the dominant energy losses consist of incomplete combustion, heat losses, and exhaust losses. Remaining losses, from flows for example, were negligible compared to these other losses.

One of the most notable findings from these works is that the exergy destroyed (an inherent unrecoverable loss due to entropy generation) increases at reduced combustion temperatures. The exergy destroyed during combustion also increases with leaner equivalence ratios. This would suggest that high combustion temperatures would increase engine efficiency; however, increases in combustion temperature also increase the heat transfer loss potential, and heat transfer also destroys exergy. This presents a paradox in optimizing engine efficiency: is it best to reduce or increase combustion temperatures?

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