



A comparison of Reactivity Controlled Compression Ignition (RCCI) and Gasoline Compression Ignition (GCI) strategies at high load, low speed conditions



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ABSTRACT

Past research has shown that Reactivity Controlled Compression Ignition (RCCI) and Gasoline Compression Ignition (GCI) combustion are promising approaches to improve efficiency and reduce pollutant emissions. However, the benefits have generally been confined to mid-load operating conditions. To enable practical application, these approaches must be able to operate over the entire engine map. A particularly challenging area is high load, low speed operation. Accordingly, the present work uses detailed CFD modeling and engine experiments to compare RCCI and GCI combustion strategies at a high load, low speed condition. Computational optimizations of RCCI and GCI combustion were performed at 20 bar gross indicated mean effective pressure (IMEP) and 1300 rev/min. The optimum points from the two combustion strategies were verified using engine experiments and were used to make the comparisons between RCCI and GCI combustion. The comparison showed that both the strategies had very similar combustion characteristics with a near top dead center injection initiating combustion. A parametric study was performed to identify the key input parameters that control combustion for the RCCI and GCI strategies. For both strategies, the combustion phasing could be controlled by the start of injection (SOI) timing of the near TDC injection. The short ignition delay of diesel fuel gave the RCCI strategy better control over combustion than the GCI strategy, but also had a simultaneous tradeoff with soot emissions. With the GCI strategy, the longer ignition delay of the gasoline fuel allowed for more air entrainment, causing lower soot emissions while giving reasonable control over combustion. Cyclic variability can be problematic at the load extremes; accordingly, the sensitivity to fluctuations in operating conditions was evaluated. Both strategies were found to be most sensitive to fluctuations in exhaust gas recirculation (EGR) rate. The GCI strategy was more sensitive to small changes in the charge conditions than the RCCI strategy, indicating that cyclic variability may be more problematic for GCI operation.

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1. Introduction

The demand for transportation energy continues to increase; however, projections show that diesel demand continues to increase, while gasoline demand remains constant or decreases [1]. In response to this projection, several researchers have proposed Gasoline Compression Ignition (GCI). Kalghatgi et al. [2,3] used a high pressure, near top dead center injection of gasoline with high levels of exhaust gas recirculation (EGR). The low auto-ignition quality of gasoline combined with high levels of EGR enabled low NO_x and soot operation at an indicated mean effective pressure (IMEP) of 14.86 bar. Sellnau et al. [4] expanded on the GCI

strategy proposed by Kalghatgi and demonstrated operation over the full load, speed range in a light-duty application. Kalghatgi et al. [5] also demonstrated that adding an early gasoline injection reduces the maximum heat release for a given IMEP. They were able to operate the engine at ~16 bar IMEP with very low soot and NO_x emissions. Ra et al. [6,7] performed a numerical study of multiple injection gasoline sprays in a heavy-duty compression ignition (CI) engine and found that improved mixing before ignition reduces the CO and UHC emissions and splitting the fuel into multiple injections was effective at reducing peak pressure rise rate (PPRR).

In addition to the strategies mentioned above, there are several other GCI strategies proposed by Marriot et al. [8,9] and Manente et al. [10,11] that show promising results. However, other researchers (e.g., Liu et al. [12]) have shown that the poor auto-

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Nomenclature

AHRR	apparent heat release rate	IMEP	indicated mean effective pressure
ASOC	after start of combustion	ISFC	indicated specific fuel consumption
ATDC	after top dead center	IVC	intake valve closing
BDC	bottom dead center	KH	Kelvin Helmholtz
BTE	brake thermal efficiency	LDEF	Lagrangian drop Eulerian fluid
CA	crank angle	LTC	low temperature combustion
CDC	conventional diesel combustion	MOGA	multi objective genetic algorithm
CFD	computational fluid dynamics	NIE	net indicated efficiency
COSSO	COmponent Selection And Smoothing Operator	NSGAI	non-dominated sorting genetic algorithm
DI	direct injection	PCI	premixed compression ignition
EGR	exhaust gas recirculation	PID	proportional integral derivative
ERC	Engine Research Center	PPRR	peak pressure rise rate
EVO	exhaust valve opening	RCCI	Reactivity Controlled Compression Ignition
FSN	filter smoke number	RNG	Re-Normalization Group
FTIR	Fourier Transform Infrared	RSM	response surface model
GA	genetic algorithm	RT	Rayleigh Taylor
GIE	gross indicated efficiency	SOI	start of injection
GRI	Gas Research Institute	TDC	top dead center
HCCI	homogenous charge compression ignition	UHC	unburned hydrocarbon

ignition qualities of gasoline can make it difficult to achieve combustion at low-load and cold start-conditions. An alternative to allow the use of gasoline in high-efficiency compression ignition engines, while retaining cold-start performance is the use of dual-fuel combustion. Diesel fuel has superior auto-ignition qualities, making low-load premixed compression ignition (PCI) operation easily achievable. However, the high reactivity of diesel fuel causes difficulty in controlling the combustion phasing at higher loads. Operating in a dual-fuel combustion mode with diesel and gasoline fuels allows blending of the relative benefits of the two fuels. Based on the work of Bessonette et al. [13] and Ingaki et al. [14], Kokjohn et al. [15–17] developed a dual-fuel PCI strategy using in-cylinder fuel blending of gasoline and diesel fuel (low and high reactivity, respectively). They named this strategy Reactivity Controlled Compression Ignition (RCCI) combustion [18]. By controlling the fuel blend, it was shown that control over the combustion phasing could be achieved. The in-cylinder fuel blending allows spatial stratification of the fuel reactivity in the cylinder, enabling control over the combustion duration. Kokjohn and Reitz [19] compared RCCI combustion and conventional diesel combustion (CDC) and found that RCCI combustion can improve the thermal efficiency by over 10% while giving an order of magnitude reduction in NOx and soot emissions. Koerberlein [20] applied the dual-fuel combustion strategy to a 6-cylinder, heavy-duty engine and found a peak brake thermal efficiency (BTE) of 49.4% with NOx emissions below the 2010 US EPA on-highway truck regulations without the need for NOx after-treatment. Benajes et al. [21] explored potential of RCCI across a wide range of loads and speeds ranging from ideal to full load and 900 rev/min to 1800 rev/min respectively with a 14.4:1 compression ratio piston. They were able to operate at 50% of full load with ultra-low NOx and soot emissions. However as the load increased, they were limited by a tradeoff between noise and soot emissions. By reducing the compression ratio to 11:1 they were able to operate at full load. Splitter et al. [22] performed an optimization study where they identified the optimum piston geometry to reduce wall heat transfer and achieved close to 60% thermal efficiency with an RCCI strategy. This piston featured an open combustion chamber with a small, shallow bowl. Wang et al. [23] performed an experimental parametric study of operating parameters to study the limiting factors of extension of upper and lower load limits of RCCI combustion.

They found that at the lower load limits, a higher fraction of diesel fuel was required to achieve good combustion efficiency. The upper load limits required a combination of high gasoline fraction and an early diesel injection with high levels of EGR to avoid excessive pressure rise rates from early combustion. However, the combination of high EGR and early SOI timing posed difficulties in controlling combustion phasing. It is to be noted that for all the strategies suggested so far, the gasoline fuel was premixed. Kavuri et al. [24] performed an optimization study to blend the benefits of RCCI and GCI combustion strategies by resorting to an RCCI strategy for the light duty drive cycle and GCI strategy for full load conditions. From the study, they proposed a light duty drive cycle RCCI strategy where the gasoline fuel was direct injected at the lightest load point and premixed at the higher loads. This allowed the RCCI engine to operate at an average of 91% gasoline over the light-duty drive cycle, reducing the diesel fuel usage to additive-type levels. At full load, the strategy transitions to a GCI operation, enabling full load range coverage with high efficiency and low NOx and soot emissions. A thorough review of existing RCCI strategies using different fuel blends can be found in Reitz and Duaraisamy [25].

Although PCI strategies show emissions and efficiency benefits over CDC, operation at high load remains a challenge. This is most evident at high loads and low engine speeds where the engine timescales are long (due to the low engine speed) and the chemistry timescales are short (due to high pressure and high equivalence ratio). The result is a mismatch in engine and chemistry timescales that makes combustion phasing control challenging. Additionally, PCI strategies also have issues with combustion control and cycle-to-cycle variation. In a recent study by Klos and Kokjohn [26] it was shown that PCI strategies like RCCI and HCCI have higher cycle to cycle variation than the CDC strategy. The higher cycle-to-cycle variation was shown to be a result of increased sensitivity of the PCI strategies to fluctuations in charge conditions such as IVC temperature and shot-to-shot fueling. Accordingly, in the present work, targeting high load, low speed, computational optimizations of the RCCI and GCI combustion strategies were performed at 20 bar gross IMEP and 1300 rev/min. The optimum points for the two combustion strategies from the optimization study were used to make the comparisons between the RCCI and GCI strategies at 20 bar and 1300 rev/min. The two combustion strategies were compared in terms of:

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