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Full Length Article

# Computational optimization of fuel supply, syngas composition, and intake conditions for a syngas/diesel RCCI engine

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ABSTRACT

By utilizing the promising alternative fuel of syngas, and the syngas/diesel dual-fuel reactivity controlled compression ignition (RCCI) is a potential combustion strategy for internal combustion engines. However, the optimal operating parameters for syngas/diesel RCCI engines under wide operating conditions have not been investigated. In this study, the operating parameters include fuel supply, syngas composition, and intake conditions of a syngas/diesel RCCI engine were optimized under wide load by integrating the KIVA-3V code and the non-dominated sort genetic algorithm II (NSGA-II). The results indicated that nitrogen oxides ($NO_x$) emissions can be controlled in considerably low levels, and the efficient combustion of the premixed syngas in the squish region can be realized with high premix ratio and early pilot injection of diesel. Equivalent indicated specific fuel consumption (EISFC) and ringing intensity (RI) are the major issues for the optimization at low and mid load, respectively. The double diesel injection strategy with the relatively late main injection timing is an effective way to both improve combustion efficiency at the low load and reduce RI at the mid load. For the double diesel injection, the ratio of pilot injection is controlled in a narrow range to provide sufficient high reactivity fuel in the piston bowl and to avoid the local high-temperature combustion region simultaneously. With the restrictions of EISFC and RI, the optimal $H_2$ fraction in the syngas is 60–80%. Based on the optimal fuel supply and intake conditions, a syngas with 75% $H_2$ and the diluent factor $C$ of 0.8 is capable of realizing the high efficiency, moderate combustion, and low emissions for the RCCI engine at full load range.

## 1. Introduction

With serious environmental pollution and rapid consumption of petroleum, the development directions of internal combustion (IC) engines are focusing on energy conservation and emission reduction in recent years. The premixed low-temperature combustion (LTC) is proposed to reduce engine emissions while maintaining the favorable fuel efficiency [1]. The advanced LTC combustion strategy includes homogeneous charge compression ignition (HCCI), premixed charge compression ignition (PCCI), and reactivity controlled compression ignition (RCCI). Due to the advantages of controlling combustion phasing and expanding operating range, RCCI has been widely investigated in recent years [2].

In order to achieve the in-cylinder reactivity stratification in RCCI, a low-reactivity fuel is premixed with air through the intake process, while a high-reactivity fuel is directly injected into the cylinder during the early compression stroke. The engine research center (ERC) at the University of Wisconsin–Madison made great achievements in the studies of RCCI engines. Kokjohn et al. [3] proposed the gasoline/diesel RCCI concept in both light- and heavy-duty engines by experiment and simulation. The results showed that low emissions and high efficiency can be simultaneously achieved by RCCI combustion. Furthermore, the combustion process of a heavy-duty hydrated (wet) ethanol/diesel RCCI engine was studied by Dempsey et al. [4] by numerical simulation. The results indicated that the fuel supply strategy controlled the local reactivity of the blended fuel in the cylinder, which determined the combustion timing and duration.

As a promising alternative gaseous fuel in place of fossil fuels, syngas is effective to reduce engine emissions [5]. The extensive sources and the various production techniques of syngas make its composition very complex. In general, syngas is mainly comprised of hydrogen (H2) and carbon monoxide (CO) in different proportions, and some methane ($CH_4$), nitrogen (N2), and carbon dioxide ($CO_2$) are also usually contained. The existence of $H_2$ in syngas accelerates the laminar flame speed and extends the flammability limit. Thus, the lean combustion of the syngas/air mixture can be realized, which is helpful for the

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**Nomenclature**

| | |
|---|---|
| $R_{pre}$ | Ratio of the premix energy of syngas relative to the total provided energy |
| *SOI-1* | Pilot injection timing (°CA ATDC) |
| *SOI-2* | Main injection timing (°CA ATDC) |
| $R_{1inj}$ | Ratio of the pilot injection relative to the total injected diesel |
| $P_{inj}$ | Injection pressure of diesel (MPa) |
| $T_{ivc}$ | Initial temperature at IVC (K) |
| $P_{ivc}$ | Initial pressure at IVC (MPa) |
| *EGR* | Exhaust gas recirculation |
| $R_{dil}$ | Diluent ratio of the non-combustible gases in syngas |
| $R_{h2\_com}$ | $H_2$ ratio relative to the combustible gas |
| $R_{n2\_dil}$ | $N_2$ ratio relative to the diluent gas |
| $E_{syngas}$ | Intake energy of syngas per cycle (J) |
| $E_{diesel}$ | Intake energy of diesel per cycle (J) |
| $E_{soi\text{-}1}$ | Intake energy of the pilot injected diesel (J) |
| $E_{soi\text{-}2}$ | Intake energy of the Main injected diesel (J) |

*Acronyms*

| | |
|---|---|
| CFD | Computational fluid dynamics |
| CI | Compression ignition |
| $CH_4$ | Methane |
| CO: | Carbon monoxide |
| $CO_2$ | Carbon dioxide |
| EISFC | Equivalent indicated specific fuel consumption |
| ERC | Engine research center |
| gRNG | Generalized Re-Normalization Group |
| HCCI | Homogeneous charge compression ignition |
| $H_2$ | Hydrogen |
| HC | Hydrocarbon |
| IC | Internal combustion |
| IMEP | Indicated mean effective pressure |
| IVC | Intake valve closing |
| KH-RT | Hybrid Kelvin Helmholtz-Rayleigh Taylor |
| LTC | Low-temperature combustion |
| MOGA | Multi-objective genetic algorithm |
| NSGA-II | Non-dominated sort genetic algorithm II |
| $NO_x$ | Nitrogen oxides |
| PCCI | Premixed charge compression ignition |
| PM | Particulate matter |
| RCCI | Reactivity controlled compression ignition |
| RI | Ringing intensity |
| SOGA | Single-objective genetic algorithm |
| TDC | Top dead center |

improvement of fuel efficiency and the reduction of nitrogen oxides ($NO_x$) and particulate matter (PM) emissions [6]. However, due to the low reactivity of syngas, the auto-ignition of the premixed syngas/air mixture is hard to be realized in compression ignition (CI) engines. Based on the duel-fuel combustion strategy, the introduction of a high-reactivity fuel with direct in-cylinder injection is potential to utilize syngas in CI engines [7].

Garnier et al. [8] established the ignition delay and combustion model for a single-cylinder syngas/diesel CI engine by varying the diesel substitution fraction with syngas. The results indicated that the engine performance was significantly affected by the diesel substitution fraction. Bika et al. [9] and Sahoo et al. [10] experimentally investigated the influence of the $H_2$/CO ratio in syngas on the combustion and emission characteristics of a syngas/diesel CI engine. It was found that the higher $H_2$ proportion leads to the increase of $NO_x$ emissions, although thermal efficiency was improved. In addition, as the major incomplete products, CO emissions were sensitive to the CO proportion in the syngas.

In order to realize the high-efficiency and clean combustion of the syngas/diesel dual-fuel CI engine, the lean operation should be employed. Recently, Shan et al. [11] and Wang et al. [12] studied the fuel injection strategy on a low-grade (with a large proportion of $N_2$ and $CO_2$) syngas/diesel RCCI engine to achieve the efficient and clean combustion. The results showed that the injection timing of diesel can effectively control the combustion phasing, and the indicated thermal efficiency reached as high as 40%. Carlucci et al. [13] experimentally investigated the injection strategy on a biodiesel/syngas dual-fuel engine to improve the engine performance. It was found that, compared with the single injection, the splitting pilot injection is able to increase the fuel efficiency and reduce all the pollutant emissions. Hagos and Aziz [14] reviewed the trend of the syngas application in engines, and it was concluded that the optimization of the operating parameters is required for syngas engines in the further study.

To improve the engine performance under wide operating conditions, numerical simulation and optimization have been widely adopted for engine design, which is beneficial for saving computational time compared with experimental methods [15]. In recent years, based on the Darwinian idea of “survival of the fittest”, the genetic algorithm (GA) has been utilized to explore the entire design space and find the best solutions for engineering optimization. For practical engines, the objectives needed to be optimized are usually more than one, and the trade-off relationship (such as $NO_x$ and soot emissions) always exist. In the single-objective genetic algorithm (SOGA), it is hard to define the merit function that represents all the objectives. In contrast, the multi-objective genetic algorithm (MOGA) is able to deal with the trade-off relationship effectively and has been widely employed in engine optimization [16,17].

In order to ensure the reliability of the genetic algorithm in engine optimization, Shi and Reitz [18] assessed the performance of three different multi-objective genetic algorithms in a heavy-duty diesel engine. The results implied that the Non-dominated Sorting Genetic Algorithm-II (NSGA-II) proposed by Deb et al. [19] is more efficient and provides more diversified populations than the other GAs. The NSGA-II was employed to optimize a heavy-duty natural gas/diesel RCCI engine by Nieman et al. [20], and the optimal control strategies were obtained. The results illustrated that the combustion of the natural gas/diesel RCCI engine was very sensitive to the injection parameters at high load. Recently, Li et al. [21] investigated the effect of the operating parameters on the combustion and emissions of a methanol/diesel RCCI engine, and the combustion process was further optimized using the NSGA-II code. The results indicated that the intake temperature and exhaust gas recirculation (EGR) rate significantly affected the engine performance and emissions, and the optimal methanol fraction can improve the combustion efficiency and emissions of the RCCI engine.

Compared with the engines with only diesel or gasoline as the fuel, the syngas/diesel RCCI engine contains much more operating parameters, which are required to be optimized for the achievement of optimal engine performance. As mentioned above, the high laminar flame speed and combustion temperature of $H_2$ in syngas are beneficial for the high-efficiency combustion of the fuel-lean mixture, but $H_2$ also contributes to the increase of engine knock and $NO_x$ emissions [10]. Meanwhile, the addition of CO, $CO_2$, and $N_2$ in syngas can reduce the high heat release rate. Therefore, the optimization of the composition of syngas and the energy fraction of syngas in RCCI engines provide promising strategies to achieve good engine performance under wide operating conditions. However, the optimization of the control strategies for the syngas/diesel RCCI has not been performed in previous studies. Especially, the optimal operating parameters significantly