Fuel 181 (2016) 878–886

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

# Experimental study of RCCI combustion and load extension in a compression ignition engine fueled with gasoline and PODE

Laihui Tong [a], Hu Wang [a,*], Zunqing Zheng [a], Rolf Reitz [b], Mingfa Yao [a]

[a] State Key Laboratory of Engines, Tianjin University, No. 92 Weijin Road, Nankai District, Tianjin 300072, PR China
[b] Engine Research Center, University of Wisconsin-Madison, 1500 Engineering Drive, Madison, WI 53705, USA

## HIGHLIGHTS

- Controllable RCCI could be achieved using PODE as the DI high reactivity fuel.
- Soot free combustion with PODE regardless of premixed ratio and DI timing.
- 1.76 MPa IMEP load can be obtained using PODE with single injection strategy.
- Ultra-low smoke and NOx are achievable with stoichiometric gasoline/PODE RCCI operation.

## ARTICLE INFO

*Article history:*
Received 13 March 2016
Received in revised form 5 May 2016
Accepted 6 May 2016
Available online 11 May 2016

*Keywords:*
Dual-fuel RCCI combustion
Fuel property
PODE
Emission
Load extension

## ABSTRACT

An experimental investigation has been conducted to explore the effects of polyoxymethylene dimethyl ethers (PODE) as the direct-injection (DI) high reactivity fuel in dual-fuel reactivity controlled compression ignition (RCCI) operation on a single-cylinder, heavy-duty diesel engine. The combustion and emission characteristics, together with the combustion phasing controllability of gasoline/diesel and gasoline/PODE RCCI operation are compared and discussed. The results show that stable and controllable RCCI operation is obtainable using PODE as the DI high reactivity fuel. Improved indicated thermal efficiency (ITE) and ultra-low smoke can be achieved with PODE, with a slight penalty, but still comparable NOx emissions. The maximum load of gasoline/PODE operation could be extended to 1.76 MPa indicated mean effective pressure (IMEP) with a single injection strategy, which is significantly higher than that of gasoline/diesel operation with an optimized double-injection strategy (1.39 MPa IMEP), while still maintaining ultra-low smoke and comparable ITE and PPRR. Stoichiometric and clean gasoline/PODE dual-fuel RCCI operation was also achievable at high load. This enables the possibility to apply a low-cost three-way catalyst to further reduce the NOx, HC and CO emissions, which offers a very competitive pathway to achieve clean and highly efficient diesel combustion.



## 1. Introduction

Reactivity controlled compression ignition (RCCI) is a potential low temperature combustion (LTC) concept to achieve clean and highly efficient combustion [1]. In this combustion mode a high octane number fuel (low reactivity) is introduced through early port injection to create a premixed charge inside the combustion chamber, while a high cetane number (CN) fuel (high reactivity) fuel is directly injected into the combustion chamber through a common rail injector. The high reactivity fuel ignites first, which triggers auto-ignition and combustion, and then the combustion gradually spreads from the high reactivity zones to the rest of the combustion chamber, following a sequential auto-ignition behavior. This results in a much slower and more controlled heat release process compared to that of homogeneous charge compression ignition (HCCI) [2]. In addition, simultaneous reductions of NOx and soot emissions can also be obtained. Therefore, this combustion concept has gained extensive attention in the internal combustion engine research community in recent years.

*Abbreviations:* AHRR, apparent heat release rate; ATDC, after top dead center; BMEP, brake mean effective pressure; CA, crank angle; CA50, the crank angle for 50% of mass fraction burnt; CO, carbon monoxide; CN, cetane number; CI, compression ignition; CFD, computational fluid dynamic; DI, direct-injection; EGR, exhaust gas recirculation; FSN, filter smoke number; HC, hydrocarbon; HCCI, homogeneous charge compression ignition; IMEP, indicated mean effective pressure; ITE, indicated thermal efficiency; LHV, low heating value; LTC, low temperature combustion; NOx, nitrogen dioxide; PPRR, peak pressure rise rate; PODE, polyoxymethylene dimethyl ethers; RCCI, reactivity controlled compression ignition; R*p*, premixed ratio; SOI, start of injection.

* Corresponding author.
*E-mail address:* wang_hu@tju.edu.cn (H. Wang).

http://dx.doi.org/10.1016/j.fuel.2016.05.037
0016-2361/

However, although RCCI has shown advantages compared to other combustion concepts, there are still obstacles that need to be resolved. One of the major issues is high load extension, which is mainly restricted by either an excessive pressure rise rate or by NOx/soot emissions. A higher premixed to DI fuel ratio (more low reactivity fuel) is usually adopted as the load increases to reduce the overall charge reactivity; however, according to the basic concept of RCCI, the premixed low reactivity charge should not be compression-ignited without the control offered by the DI high reactivity fuel. Therefore, under high load conditions, there are upper limits for the premixed ratio, otherwise, gasoline HCCI-like combustion occurs, which results in an excessive pressure rise rate. In addition, high soot and NOx emissions become issues that must be considered if a higher DI ratio is adopted to suppress the pressure rise rate. Also, relatively high CO and HC emissions due to the reduced combustion efficiency resulting from the premixed low reactivity fuel, combined with the lower exhaust temperature, pose higher requirements on aftertreatment devices. In addition, since massive exhaust gas recirculation (EGR) is usually used as NOx and combustion control measures, high load extension is also limited by the air fuel ratio (equivalence ratio), otherwise penalized combustion and thermal efficiencies will be observed.

In order to achieve high/full load RCCI operation, various control parameters, including injection strategy optimization, intake temperature and boosting, EGR and variable valve timing, etc., have been studied to explore the load extension strategy in RCCI combustion [3–9]. One way to extend high load RCCI operation is to enhance the in-cylinder mixture stratification, which can be achieved by injection strategy and system optimization. For example, stronger in-cylinder stratification can be obtained by retarding the SOI timing of the DI high reactivity fuel. Ma et al. [3] showed that the high load limit could be extended from 1.02 MPa IMEP with early single injection to 1.39 MPa IMEP with a late second DI timing (double-injection) in gasoline/diesel dual-fuel RCCI combustion. However, the high soot and NOx emissions with late injection limit further extension of the load. Alternatively, stronger mixture stratification can also be obtained by the addition of a second DI injector for the low reactivity fuel. Lim and Reitz [10] utilized a second gasoline DI injector in addition to the diesel DI injector to introduce stronger mixture stratification to extend the upper load. Through computational fluid dynamic (CFD) simulations, stable RCCI load could be extended up to 2.1 MPa IMEP. However, a third injection system would be necessary with this approach, together with more control and calibration parameters, which greatly increase the complication of the control system.

Another effective approach to optimize the combustion and to extend the load limit is fuel property optimization. Previous studies have shown that the reactivity difference between gasoline and diesel and the physical properties of the premixed gasoline fuel favor the application of these two fuels in RCCI operation [11]. It is expected that enlarging the reactivity difference or gradient between the premixed low reactivity and DI high reactivity fuels could be a very effective way for RCCI combustion control and load extension. This can be done by further reducing the reactivity of the premixed low reactivity fuel, for example.

Various low reactivity fuels, including natural gas [12–16], methanol/ethanol [17–23] and butanol [24–28], have been previously studied to explore their effects on load extension in RCCI combustion. The common conclusion is that stable and extended RCCI operation can be achieved with these low reactivity alternative fuels, and alcohols have shown high application prospects in RCCI because of their high latent heat of vaporization and low reactivity. For example, Nieman et al. [12] numerically demonstrated that 2.2 MPa IMEP load can be obtained by applying a late second injection timing strategy with methane as the premixed low reactivity fuel. Curran et al. [22] showed that 0.88 MPa BMEP was achievable with E85/diesel, which was not obtainable due to high pressure rise rates and unstable combustion with gasoline/diesel in their tests at 2600 r/min engine speed in a multi-cylinder light-duty diesel engine. Zhang et al. [23] was able to extend the maximum load up to 1.9 MPa BMEP with E85/diesel in a heavy duty diesel engine. The numerical work conducted by Wang et al. [27] showed that i-butanol/diesel was able to achieve similar loads as compared to gasoline/diesel (1.46 MPa IMEP). In addition, Liu et al. [28] showed that stable RCCI operation can be realized with n-butanol/bio-diesel fuels, and 1.28 MPa IMEP load can be achieved while still maintaining quite low NOx and soot emissions.

However, although reducing the reactivity of the premixed fuels can effectively enlarge the reactivity gradient to extend the load limit, there are still drawbacks with this approach. Reduced combustion efficiency, along with high CO and HC emissions are usually observed under low load conditions with these low reactivity fuels [1]. In addition, a higher DI ratio was also required to ensure the auto-ignition and combustion processes, resulting in higher NOx, and sometimes more soot emissions. Therefore, it is desirable to further explore the effects of fuel properties on RCCI combustion, emissions and load extension.

PODE ($CH_3O(CH_2O)_nCH_3$) is an emerging alternative fuel that can be used in diesel engines. The major physical properties of gasoline, diesel and PODE are listed in Table 1. As can be seen in this table, the unique properties of PODE (no C–C bond, high oxygen content and high CN) indicate that it has significant potential to achieve highly efficient and clean combustion and could be a competitive alternative fuel for diesel engines. Pellegrini et al. [29,30] and Liu et al. [31] found that PODE showed the capability to greatly reduce soot emissions in conventional combustion diesel engines. However, due to the significantly different properties of PODE compared to those of diesel, re-optimization of the injection parameters and also the combustion process are usually needed to fully utilize its advantages.

The properties of PODE also favor its application in dual-fuel RCCI operation. Firstly, the reactivity gradient between the premixed and DI fuels can be enlarged using gasoline/PODE compared to gasoline/diesel. In this case, less PODE is required to ignite the premixed gasoline fuel due to its significantly higher CN, combined with its lower low heating value (LHV). Thus the initial energy released by the DI PODE is considerately lower than diesel, which is potentially helpful for PPRR and NOx reduction in RCCI operation. Secondly, since the LHV of PODE is lower than diesel (36% less per unit volume), a prolonged injection duration is required to maintain the same energy through direct-injection compared to diesel. Therefore, the heat release rate can actually be controlled by the injection event through injection rate control, especially under high DI ratio conditions. This results in lower PPRR and

**Table 1**
Major physical properties of diesel, gasoline and PODE [31,32].

| Fuel | Diesel | Gasoline | PODE (wt) |
|---|---|---|---|
| Molecule formula | $C_{12}$–$C_{25}$ | $C_4$–$C_{12}$ | $PODE_3$ 44.8%, $PODE_4$ 28.24% $PODE_5$ 17.09%, $PODE_6$ 9.87% |
| Boiling point (°C) | 190–340 | 25–215 | 150–240 |
| Density (g/cm$^3$@25 °C) | 0.834 | 0.763 | 1.0471 |
| Cetane number | 51 | – | 75.5 |
| Octane number | – | 95 | – |
| Low heating value (MJ/kg) | 42.6 | 42.8 | 21.77 |
| Oxygen content (wt%) | – | – | 47.95 |
| Kinetic viscosity (MPa s) | 3.24 | 0.55–0.74 | 1.11 |