

Experimental Study on High-Load Extension of Gasoline/PODE Dual-Fuel RCCI Operation Using Late Intake Valve Closing

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ABSTRACT

The dual-fuel Reactivity Controlled Compression Ignition (RCCI) combustion could achieve high efficiency and low emissions over a wide range of operating conditions. However, further high load extension is limited by the excessive pressure rise rate and soot emission. Polyoxymethylene dimethyl ethers (PODE), a novel diesel alternative fuel, has the capability to achieve stoichiometric smoke-free RCCI combustion due to its high oxygen content and unique molecule structure. In this study, experimental investigations on high load extension of gasoline/PODE RCCI operation were conducted using late intake valve closing (LIVC) strategy and intake boosting in a single-cylinder, heavy-duty diesel engine. The experimental results show that the upper load can be effectively extended through boosting and LIVC with gasoline/PODE stoichiometric operation. With the retarding of LIVC timing and increase of cyclic fuel quantity, higher boosting pressure and lower Exhaust Gas Recirculation (EGR) ratio were required to maintain sufficient available oxygen. The upper load of gasoline/PODE RCCI operation could be extended up to 23 bar indicated mean effective pressure (IMEP), while still maintaining ultra-low smoke/NO_x emissions and acceptable peak in-cylinder pressure and pressure rise rate (PRR). In addition, stoichiometric combustion also enables the application of a low-cost three-way catalyst to further reduce HC and CO emissions. However, LIVC results in slight reduction of indicated thermal efficiency (ITE) due to the lower effective compression ratio and more incomplete combustion with stoichiometric operation, thus further combustion optimization is necessary for ITE improvement. The study reveals that gasoline/PODE RCCI offers a very competitive pathway to achieve clean and highly efficient combustion over the full load conditions.

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INTRODUCTION

The dual-fuel RCCI combustion mode, which is currently one of the attractive novel combustion concepts, has the capability to achieve high efficiency and low emissions over a wide range of operating conditions [1, 2]. In this combustion concept, a premixed low reactivity fuel (high octane number), such as gasoline, is introduced through port injection, while a high reactivity (high cetane number (CN)) fuel, such as diesel, is directly injected into combustion chamber to create the ignition source. The in-cylinder mixture concentration stratification can be controlled by the direct-injection (DI) injection strategy, while the mixture reactivity stratification can be controlled by both the ratio between the premixed low reactivity fuel and DI high reactivity fuel, and the DI injection strategy. The auto-ignition event is actually controlled by the DI timing, while both the combustion phasing and combustion reaction rate, expressed as the CA50 (Crank angle of 50% accumulative heat release) and heat release rate (HRR), can be controlled by both the mixture concentration and reactivity stratifications. From the combustion theory aspect, the in-cylinder auto-ignition and combustion are essentially controlled by the in-cylinder thermodynamic state,

mixture composition, distribution and reactivity, thus any factors that affect these parameters will have impact on the following combustion process [3, 4].

Numerous studies have been conducted to explore the effects of various control parameters on RCCI combustion, emissions and load extension, including the premixed ratio, DI injection strategy, intake pressure/temperature, combustion chamber geometry, alternative fuels, EGR and so on [5, 6, 7, 8, 9, 10, 11]. The basic idea is to improve the thermal efficiency while still maintain low PRR and emissions over wide operating conditions. Reitz et al. at Engine Research Center has conducted extensive studies on the RCCI combustion concept, and their results showed that up to 56% indicated thermal efficiency can be obtained with this combustion concept, together with extremely low emissions [12]. It has also been demonstrated that the combustion phasing controllability of RCCI (the response of CA50 to control parameters, such as start of injection (SOI) timing and premixed ratio) shows advantages compared to the Homogeneous Charge Compression Ignition (HCCI) and Partially

Premixed Combustion (PPC) at various conditions [13]. Therefore, RCCI has been regarded as one of the most competitive concepts to achieve clean and high efficient combustion.

However, there are still obstacles to operate gasoline/diesel dual fuel RCCI at high or full loads, mainly due to the limitations of peak pressure rise rate (PPRR) and soot emission at high loads [14]. In order to control the heat release rate, usually very small amount of DI diesel fuel can be used at high load. Even though, the in-cylinder temperature and pressure at high load still favor the reaction of both premixed gasoline and DI diesel fuels, which means that once the auto-ignition occurs, the combustion actually exhibits a HCCI-like combustion event due to the nearly homogeneous charge with high equivalence ratio. In this case, increase the DI diesel fraction can be helpful for PPRR suppression, however, the soot emission become another issues under such conditions (NO_x can be controlled by EGR). To solve this issue, injection strategy optimization has been used to achieve optimal mixture distribution to extend the high load limit. For example, Ma et al., explored the effects of multi-injection strategy on RCCI load extension, and it is demonstrated that 13.9 bar IMEP load can be achieved with double-injection strategy (an early pilot injection combined with a late second injection) using commercial gasoline and diesel [7]. The late second injection was used to increase the in-cylinder stratification to suppress the PPRR. Even though, further load extension is difficult with such configurations.

From the nature of RCCI combustion, enhancing either the in-cylinder mixture concentration stratification or the reactivity gradient can be helpful for load extension. This can be achieved by several approaches. Direct injection of the low reactivity fuel to create stronger mixture stratification can be one possible measure. In addition to the port injection premixed gasoline and DI diesel fuel, part of gasoline is also introduced into the combustion chamber through direct injection. In this case, stronger stratification exists prior to auto-ignition, which has been shown to be able to extend the load up to 21 bar IMEP by Lim and Reitz [15]. However, one extra high pressure fuel injection system will be required with this approach, which greatly increases the cost and control complexity of the engine system. Another effective measure is to enlarge the charge reactivity gradient, which can be done by replacing the premixed gasoline fuel with other fuels with even lower reactivity, such as natural gas (methane), methanol, ethanol, butanol, et al [11, 16, 17, 18]. The common characteristics of these premixed fuels are the significantly higher octane number (lower reactivity) compared to gasoline. Due to the stronger reactivity gradient, the combustion reaction rate can be effectively controlled, thus much higher load can be achieved. Niemen and Reitz et al. has shown that 22 bar IMEP load can be obtained with natural gas/diesel dual-fuel RCCI operation [16]. In addition, extra benefits can be obtained when methanol and ethanol were used as the premixed fuels, mainly because of their high latent heating values, which could greatly reduce the intake charge temperature due to the cooling effects, and thus are helpful for further load extension [5, 17]. Even though, the PPRR and soot issues remain to some extent; in addition, the application of these high octane number fuels may induce combustion stability problem under low load conditions, thus further studies are needed.

In addition to use even higher octane number fuels as premixed fuel to create stronger reactivity gradient, it is also interesting to explore the characteristics of using higher cetane number (CN) fuels as DI fuel to create stronger reactivity gradient within in this combustion concept. Also, as mentioned above, soot emission prohibits the further increase of DI fraction for PPRR suppression and load extension, thus oxygenated fuels with high cetane number should be able to resolve both the PPRR and soot emission issues at high loads. From this point of view, PODE ($\text{CH}_3\text{O}(\text{CH}_2\text{O})_n\text{CH}_3$), a potentially novel diesel alternative fuel, has been taken into consideration for RCCI operation and load extension [19].

The detailed comparison of major properties between gasoline, diesel and PODE can be found in [19, 20]. It is seen that the properties of PODE greatly favor its application in dual-fuel RCCI operation. The high CN of PODE enlarge the reactivity gradient for combustion control. Its unique molecular structure with no C-C bond and high oxygen content indicate its capability for soot suppression. It was also found that due to its significantly lower low heating value (LHV) compared to diesel, the heat release rate can actually be controlled by the injection event through injection rate control, especially under high DI ratio conditions, which is also beneficial for PPRR suppression and load extension [19]. These factors suggest that PODE has great potential for RCCI operation and load extension. The experimental results presented by Tong et al. have shown that 17.6 bar IMEP load can be obtained using gasoline/PODE with single late injection strategy, within which a smoke-free stoichiometric combustion could be achieved, together with acceptable UHC and CO emissions [19]. However, further load extension was limited by the boost pressure and peak in-cylinder pressure (effective compression ratio).

As one of the representative Variable Valve Timing (VVT) strategies, the LIVC strategy is an effective measure to control the in-cylinder thermodynamic conditions by changing LIVC timing in internal combustion engines. One of the advantage of this technology is to adjust the effective compression ratio, by doing which the in-cylinder temperature and pressure can also be adjusted according to the operating conditions. This approach has already been used in various combustion modes for combustion and emission improvements [21, 22], which should be helpful to reduce the PPRR and peak pressure issues in dual-fuel RCCI operation at high loads.

Therefore, in this paper, gasoline/PODE dual-fuel RCCI load extension has been conducted using LIVC timing, intake boosting and EGR strategy. Previous study has already shown that stoichiometric operation is achievable with gasoline/PODE, thus during the experiments, the excess air fuel ratio is maintained close to unity through intake pressure and EGR rate control, which enables the possibility to adopt the conventional three-way catalyst aftertreatment for further emission reduction [19]. With such configurations, the effects of LIVC timing on gasoline/PODE RCCI combustion and emission characteristics, including indicated thermal efficiency, combustion phasing, PPRR, major emissions etc., will be explored firstly, followed by the effects of boost pressure, based on which the control strategy for PODE/gasoline dual-fuel RCCI high load extension will be discussed.

EXPERIMENTAL SETUP

The experiments were conducted on a modified six-cylinder heavy-duty diesel engine, in which the sixth cylinder was separated from the other five cylinders as the testing cylinder, which was equipped with separate intake and exhaust systems. An external air compressor was used to provide the boost pressure while an intake cooler was used to control the intake temperature. An exhaust back pressure valve and EGR valve were used to control the EGR rate. PODE was injected into the combustion chamber with a high pressure common rail injection system, while a gasoline port fuel injection (PFI) injector was mounted on the intake manifold to create the premixed gasoline charge, both with flexibly adjustable injection control systems. The schematic experimental setup is shown in Fig. 1, and the engine specifications and experimental limits during the experiments are shown in Table 1.

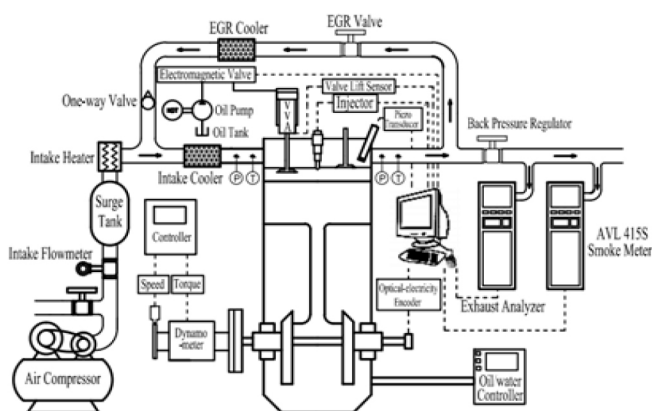


Figure 1. Experimental setup

The experimental instrumentations in the experiments are listed in Table 2. The apparent heat release rate (AHRR), ignition delay (defined as the crank angle between SOI and 10% accumulated heat release, CA10), combustion phasing (CA50) and combustion duration (defined as the interval between CA10 and CA90), etc., all were calculated from the ensemble-averaged in-cylinder pressure from 100 consecutive cycles.

Table 1. Engine specifications and experimental limits

Bore/stroke	105/125 mm
Connecting rod length	210 mm
Bowl volume	1.08 L
Geometric CR	15.8:1
IVC timing	-133 CA ATDC
EVO timing	125 CA ATDC
Port fuel injector	4 holes, 15°
DI fuel injector	8 holes, 150°
Max DI Pressure [MPa]	16.0
PPRR [bar/°CA]	15.0
COV _{IMEP} [%]	5.0

The engine operating conditions are listed in Table 3. During the experiments, the excess air fuel ratio was controlled at around 1.0 by control both the intake pressure and EGR rate based on the authors'

previous study [19]. The premixed ratio (R_p) in this study is energy-based, i.e., the fraction of premixed energy compared to that of the total fuel energy. Since smoke free combustion can be obtained with PODE regardless of the DI ratio, thus significantly higher DI ratio of PODE compared to diesel/gasoline operation was adopted in the experiments (40-45%) to suppress the PPRR for load extension. A late single injection strategy was used for DI PODE in the experiments. In order to maintain constant excess air fuel ratio with higher load and retarded LIVC timing, much higher intake pressure was required. However, limited by both the air compressor capability and PFI pressure, the maximum intake pressure was kept to be lower than 0.37 MPa, which is already significantly higher than normal conditions. The experiments started with a cyclic fuel quantity of 100 mg equivalent diesel mass, and was gradually increased up to 137 mg/cycle, corresponding to around 23 bar IMEP load. Details about the load extension process will be discussed in the following section.

Table 2. Experimental instrumentation

Parameters	Model
Pressure sensor	Kistler 6125C
Charge amplifier	Kistler 5018
Shaft encoder	Kistler 2614A4
NOx, CO, UHC	Horiba MEXA
Excess A/F ratio	7100DEGR
EGR	
Smoke	AVL 415S
Intake flow meter	Vortex-shedding
Fuel flow meter	AVL 733S/FCM01

Table 3. Experimental operating conditions

Parameter	Value
Engine speed [r/min]	1500
Intake pressure [MPa]	0.22-0.37
Cyclic fuel mass [mg]	100-137
Intake temperature [K]	313.0
DI pressure [MPa]	80.0
PFI pressure [MPa]	0.38
Premixed fuel	Gasoline
DI fuel	PODE
DI injection strategy	Single

In the experiments, a VVT device, which is capable of achieving late intake valve closing, was used to adjust the effective compression ratio.

Fig. 2 shows representative valve profiles for different late intake valve closing timings from the experiments, Fig. 3 shows the effective compression ratio as a function of various LIVC timings, which was calculated with a GT-Power model for this engine. It is seen in these two plots that the effective compression ratio shows a nearly linear correlation as the IVC timing retards, and the effective compression ratio can be reduced to around 9.5 when the IVC timing was retarded by 55 °CA, which was thought to be very helpful for high load extension. However, such low compression ratio would have negative effect on indicated thermal efficiency, which will also be shown and discussed later.