

Experimental Study on High-Load Extension of PODE/Gasoline Dual-Fuel RCCI 1 Postprint

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Abstract

A novel oxygenated fuel, PODE, was employed as the direct injection fuel to realize PODE/gasoline dual-fuel RCCI combustion. The effects of PODE on RCCI dual-fuel combustion and emissions under various boundary conditions were investigated, and experimental studies on high-load extension were conducted in conjunction with a late intake valve closing (LIVC) strategy. The results indicate that: compared with diesel fuel, PODE as the direct injection fuel can achieve lower soot emissions while effectively improving both combustion efficiency and thermal efficiency; reducing the excess air ratio (λ) can effectively suppress the peak combustion rate, while the soot emissions of PODE/gasoline RCCI are insensitive to λ , and extremely low soot emissions can still be achieved even under fuel-rich conditions ($\lambda < 1$), however, the region near the equivalence ratio can lead to CO deterioration; late intake valve closing can reduce in-cylinder pressure and peak combustion rate, but excessively retarded intake valve closing timing reduces the intake air quantity, leading to increased NO_x emissions; combining late intake valve closing with high boost pressure to achieve stoichiometric combustion can extend the high-load range to 2.31 MPa IMEP, without causing significant deterioration in brake thermal efficiency.

Full Text

Experimental Study on High-load Extension of PODE/Gasoline Dual-fuel RCCI Operation

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Abstract

This study experimentally investigates the high-load extension of PODE/gasoline Reactivity Controlled Compression Ignition (RCCI) operation in a single-cylinder heavy-duty diesel engine under various boundary conditions using a Late Intake Valve Closing (LIVC) strategy. The results demonstrate that compared to diesel, using PODE as the direct-injection fuel achieves substantially lower smoke emissions while improving combustion efficiency and thermal efficiency. Reducing the excess air ratio (λ) effectively suppresses peak heat release rates. Notably, PODE/gasoline RCCI smoke emissions are insensitive to λ , maintaining ultra-low smoke even under fuel-rich conditions ($\lambda < 1$), though stoichiometric operation leads to deteriorated CO emissions. The LIVC strategy reduces in-cylinder pressure and peak combustion rates; however, excessively retarded intake valve closing timings decrease intake charge, causing increased NOx emissions. By combining LIVC with high boost pressure to achieve stoichiometric combustion, the high-load operating range extends to 2.31 MPa IMEP without significant deterioration of indicated thermal efficiency.

Keywords: PODE; dual-fuel; RCCI; LIVC; load extension

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Introduction

Internal combustion engines serve as the dominant power source in national economic operations and represent the primary consumer of petroleum and source of urban pollutant emissions [1,2]. With increasingly severe global ecological and environmental challenges and escalating energy crises, emission regulations for internal combustion engines are becoming progressively stringent worldwide, including in China. Particularly, growing concerns about ecological issues caused by CO emissions demand that the engine industry continuously improve thermal efficiency while substantially reducing harmful gas emissions [3,4]. To meet future ultra-low emission regulations and thermal efficiency improvement requirements, numerous efficient and clean novel combustion modes have been proposed in recent years, accompanied by in-depth exploration of combustion optimization theories and control technologies. Consequently, novel combustion technologies have emerged as a hot topic and frontier in international advanced internal combustion engine combustion research [5-7].

The diesel/gasoline dual-fuel RCCI combustion mode achieves reactivity and concentration stratification control through port injection of high-octane gasoline fuel and direct injection of high-cetane diesel fuel near top dead center,

where the diesel ignition initiates combustion of the premixed high-octane mixture. RCCI can modulate the overall reactivity of the in-cylinder charge by varying the injection ratio of the two fuels according to different load demands. Additionally, the in-cylinder direct injection strategy simultaneously creates local reactivity and concentration stratification, which, when coupled with appropriate Exhaust Gas Recirculation (EGR), effectively controls ignition timing, combustion phasing, and reaction rates. Therefore, compared to Homogeneous Charge Compression Ignition (HCCI) and other novel combustion modes, RCCI effectively extends the high-load upper limit [8-10]. However, further extending the high-load operating range to achieve efficient and clean combustion across all load conditions for diesel/gasoline RCCI remains challenging. Previous studies [11] indicate that increasing load typically requires raising the gasoline port injection proportion to reduce overall charge reactivity for combustion phasing control, but the premixed gasoline must be prevented from auto-igniting before diesel injection. Simultaneously, to enhance fuel reactivity and concentration stratification at high loads, EGR introduction and port injection quantities must be limited. As load further increases, increased direct diesel injection raises smoke emissions, and achieving higher loads under RCCI requires greater intake boost capability due to air-fuel ratio limitations. Thus, diesel fuel is not the ideal direct-injection fuel for RCCI combustion mode.

Polyoxymethylene dimethyl ethers (PODE, $\text{CH}_2\text{O}(\text{CH}_2\text{O})_n\text{CH}_2$) represent a novel alternative diesel fuel. Their unique physicochemical properties (absence of C-C bonds, high oxygen content, and relatively high cetane number) effectively reduce soot emissions in diesel engines [12-14]. However, due to their significantly lower volumetric heating value compared to diesel, longer injection durations are required per unit heat value, necessitating optimization of the fuel delivery system and injection strategies, which makes direct application in conventional diesel engines difficult. For RCCI combustion mode, however, the direct injection proportion is relatively small, allowing conventional fuel systems to meet injection requirements. Moreover, the increased direct-injection volume per unit heat value facilitates in-cylinder mixture stratification and control of multiple injection strategies, while the longer injection duration helps strengthen control over ignition and combustion processes. Based on this rationale, this study employs PODE as the direct-injection fuel to explore the combustion and emission characteristics of PODE/gasoline dual-fuel RCCI and its potential for high-load extension.

1.1 Experimental Fuels and Engine Setup

This study utilizes commercial RON 95 gasoline for port injection and PODE with a cetane number of 75.5 for direct injection. The physicochemical properties of gasoline and PODE are presented in .

The experiments were conducted on a six-cylinder turbocharged intercooled, electronically controlled high-pressure common-rail diesel engine with a single-cylinder displacement of 1.08 L. The sixth cylinder was modified as the test

cylinder with independent intake and exhaust systems and fuel delivery, while the remaining five cylinders remained unchanged. The engine specifications are listed in , and the engine test bench schematic is shown in [Figure 1: see original paper]. To achieve in-cylinder mixing of two fuels with different properties, PODE and gasoline employ two independent fuel injection systems. The PODE direct-injection system, developed in-house, enables flexible control of injection frequency, timing, duration, and pressure. This study employs single PODE injection with a fixed injection pressure of 80 MPa. Gasoline is injected through a port fuel injector installed in the intake manifold, with an independently developed control system allowing flexible adjustment of injection duration and timing. In this study, gasoline injection begins at intake valve closing with a fixed pressure of 0.38 MPa, ensuring formation of a well-homogeneous mixture. Cylinder pressure is measured by a Kistler-125C pressure transducer installed in the third cylinder, with real-time data acquisition and combustion analysis performed by an independently developed system. Gaseous emissions are measured using a HORIBA MEXA-7100DEGR multi-component gas analyzer, while smoke emissions are measured with an AVL 415s filter paper smoke meter.

1.2 Experimental Methodology

In this study, the cycle fuel injection quantity (mg/cyc) for dual-fuel tests is defined as the equivalent gasoline quantity calculated based on the total heat energy of fuel entering the cylinder using gasoline's heating value. IMEP represents the indicated mean effective pressure calculated over the compression and expansion strokes, and the gasoline proportion (R_p) is defined as the ratio of gasoline heat value to the total heat value of fuel entering the cylinder.

The test speed was selected as 1500 r/min, with intake temperature controlled at (38 ± 1) °C, engine coolant temperature at (85 ± 1) °C, PODE temperature at (30 ± 0.5) °C, and gasoline temperature at (25 ± 1) °C. To ensure accuracy and reliability, gaseous emissions data represent the average of continuous 30-second sampling after 2 minutes of stable engine operation, while smoke emissions represent the average of four consecutive measurements. All data were obtained under the following constraints: coefficient of variation (COV) < 5%, maximum cylinder pressure P_{max} 16 MPa, and maximum pressure rise rate M_{PRR} 1.2 MPa/°CA.

2.1 Comparison of Diesel/Gasoline and PODE/Gasoline RCCI Combustion Modes

[Figure 2: see original paper] compares the combustion characteristics when diesel and PODE are used as direct-injection fuels, with a cycle fuel quantity of 50 mg/cyc equivalent gasoline, gasoline port injection proportion R_p of 80%, intake pressure of 0.2 MPa, and CA50 controlled at 7 °CA ATDC. Under late-injection RCCI combustion mode, both diesel/gasoline and PODE/gasoline RCCI exhibit distinct two-stage heat release profiles. The difference is that PODE does not show a low-temperature heat release stage but rather a dip

in the heat release rate curve, attributed to greater latent heat of vaporization due to higher injection quantity. Due to PODE's higher cetane number, its main injection timing is relatively retarded while injection duration is extended, resulting in a shorter ignition delay. However, its first-stage premixed heat release peak is significantly higher than diesel's, primarily because PODE's better volatility enables faster mixing rates and its higher ignition energy can ignite more premixed gasoline mixture. The higher premixed heat release peak also results in slightly higher peak cylinder pressure compared to diesel.

[Figure 3: see original paper] compares emission characteristics when diesel and PODE serve as direct-injection fuels. Both fuels achieve extremely low smoke and NOx emissions across various EGR rates. Although PODE has a shorter ignition delay and larger injection volume, its high oxygen content of 48% effectively suppresses soot precursor formation, enabling near-zero smoke emissions. Due to higher injection quantity, the latent heat of vaporization effect is more pronounced, helping reduce peak cylinder temperature. Combined with its mixing rate effects, PODE's NOx emissions are slightly lower than diesel's. HC and CO emissions are relatively high under RCCI combustion mode, but PODE's high oxygen content and higher ignition energy effectively improve incomplete combustion product emissions, particularly evident under high EGR rates of 55%, resulting in slightly improved thermal efficiency.

2.2 Effects of on Gasoline/PODE RCCI Combustion and Emissions

[Figure 4: see original paper] illustrates the combustion characteristics of PODE/gasoline RCCI under different excess air ratios (λ), with a cycle fuel quantity of 80 mg/cyc, intake pressure of 0.22 MPa, gasoline proportion R_p of 80%, and CA50 controlled at approximately 8 °CA ATDC through main injection timing. As EGR rate increases and λ decreases, the corresponding main injection timing advances, but the ignition point does not advance significantly, resulting in extended ignition delay. The first-stage heat release peak increases with advanced main injection timing, effectively suppressing the second-stage main heat release peak. Combustion duration extends significantly, resulting in milder combustion. Particularly at $\lambda = 0.97$, the excessively early injection timing produces a high-premixing single-peak heat release profile, with low-temperature reaction heat release reappearing. Thus, from a high-load extension perspective, reducing λ as much as possible is necessary to control combustion rates.

presents the main combustion and emission parameters of PODE/gasoline RCCI at different λ values. As λ decreases, smoke emissions remain extremely low, showing no deterioration even under rich combustion conditions ($\lambda < 1$), indicating PODE's inherent resistance to soot formation. Due to increased EGR rates, NOx emissions decrease significantly with decreasing λ . However, HC and CO emissions increase with decreasing λ , with CO emissions rising sharply near stoichiometric conditions, causing combustion efficiency deterioration. Nevertheless, stoichiometric combustion enables simpler aftertreatment devices such

as three-way catalysts to control HC/CO. Although thermal efficiency decreases slightly due to combustion deterioration, it remains high at >44.5%. Comparatively, is more effective at suppressing maximum pressure rise rate, making it a viable approach for high-load extension.

2.3 Combustion and Emission Characteristics at Different Late Intake Valve Closing Timings

The Late Intake Valve Closing (LIVC) strategy reduces the effective compression ratio and suppresses excessively fast heat release rates, representing an effective technical approach for extending low-temperature combustion to high loads in diesel engines. This study employs an independently developed electro-hydraulic variable valve system to control intake valve closing angles. [Figure 5: see original paper] shows the intake valve lift profiles for different LIVC timings, while [Figure 6: see original paper] illustrates the effect of LIVC timing on combustion. The test conditions include a cycle fuel quantity of 100 mg/cyc equivalent gasoline, intake pressure $P_{in} = 0.22$ MPa, $R_p = 60\%$, $\lambda = 1.0$, and CA50 controlled at 11 °CA ATDC. As intake valve closing timing is retarded, peak heat release rate decreases and maximum cylinder pressure is effectively suppressed. Particularly at an LIVC angle of 55 °CA, both maximum cylinder pressure and peak heat release rate are significantly lower than the baseline valve profile, effectively overcoming cylinder pressure and pressure rise rate limitations during high-load extension.

[Figure 7: see original paper] shows the effect of LIVC timing on emissions. Due to PODE' s inherent low-soot characteristics, LIVC timing has minimal impact on smoke, achieving near-zero smoke emissions across all timings. However, as intake valve closing timing is retarded, NO_x emissions increase rapidly despite significantly reduced peak heat release rates. This occurs because retarded intake valve closing substantially reduces intake charge. To maintain stoichiometric combustion ($\lambda = 1$), corresponding EGR introduction decreases, reducing total in-cylinder working fluid mass and specific heat capacity, thereby increasing average cylinder temperature and NO_x emissions. HC and CO emissions show similar trends, initially increasing then decreasing. With retarded intake valve closing, reduced compression density extends PODE spray penetration, increasing wall-impinged fuel quantity and fuel distribution in low-temperature peripheral combustion zones, while milder and slower combustion elevates HC and CO. However, as LIVC timing is further retarded, increased average cylinder temperature enhances late-cycle oxidation, causing HC/CO to improve as temperature becomes the dominant factor.

2.4 High-load Extension of Gasoline/PODE RCCI

The LIVC strategy effectively suppresses combustion rates and peak pressure, enabling higher intake pressures for high-load extension. presents the maximum load limits at various intake pressures with an LIVC angle of 55 °CA. Due to PODE' s low-soot characteristics, peak cylinder pressure and pressure rise rate

become the key limiting factors. The experiments controlled maximum cylinder pressure $P < 16$ MPa and maximum pressure rise rate $MPPR \approx 1.2$ MPa/°CA. To enhance stratification and combustion control through injection duration, the direct-injection proportion was increased by controlling R_p in the lower range of 53%-56%.

[Figure 8: see original paper] shows the cylinder pressure and heat release rates at maximum loads achieved under various intake pressures. Increased direct-injection proportion effectively controls the second-stage heat release peak, overcoming pressure rise rate limitations and enabling stoichiometric combustion, which facilitates aftertreatment of incomplete combustion products using three-way catalysts. Intake charge becomes the primary factor limiting fuel quantity increase. As intake pressure increases, peak cylinder pressure rises significantly, restricting further load increase and necessitating further retarded LIVC timing for larger loads.

[Figure 9: see original paper] illustrates emission characteristics across the high-load extension range. Despite high direct-injection proportion and excessively long injection duration causing fuel spray to penetrate into the flame, near-zero smoke emissions are maintained. High intake density and large EGR introduction effectively control average cylinder temperature, resulting in low NOx emissions. However, near stoichiometric conditions leads to high incomplete combustion products, particularly CO emissions, which are highly sensitive to small fluctuations. Consequently, indicated thermal efficiency is somewhat affected but remains within a reasonable range above 40%.

Conclusions

This study investigated PODE/gasoline RCCI combustion and emission characteristics under various boundary conditions at 1500 r/min using PODE as the direct-injection fuel, and experimentally explored high-load extension through high boost pressure combined with LIVC strategy. The main conclusions are:

1. Compared to diesel/gasoline RCCI, PODE/gasoline RCCI achieves lower smoke emissions while significantly improving combustion efficiency and thermal efficiency.
2. Mixture concentration effectively controls heat release rates. Near stoichiometric conditions ($\phi \approx 1$), combustion duration extends and maximum pressure rise rate decreases substantially, while achieving ultra-low smoke and NOx emissions with effective thermal efficiency reaching 44.5%-45.2%. However, HC and CO emissions are more sensitive to ϕ and deteriorate under these conditions.
3. The LIVC strategy reduces peak cylinder pressure and combustion rates, but decreased intake charge leads to increased NOx emissions. Insufficient intake air becomes the primary factor limiting high-load extension.
4. Stoichiometric PODE/gasoline RCCI combustion achieves ultra-low

smoke/NO_x emissions and effectively extends the high-load operating range. With an LIVC timing of 55 °CA, the maximum load extends to 2.31 MPa IMEP while maintaining high indicated thermal efficiency.

References

- [1] YAO Mingfa, LIU Haifeng. Review and Prospect of the Combustion Technology of Homogeneous Charge Compression Ignition and Low Temperature Combustion[J]. Chinese Journal of Automotive Engineering, 2012, 2(2):79-90.
- [2] HUANG Zuohua. Research and Development of Current Situation and Frontier for Energy-saving and Clean Utilization of Internal Combustion Engines[J]. Automotive Safety and Energy, 2010, 1(2): 89-97.
- [3] Fuel Consumption Evaluation Methods and Targets for Passenger Cars[S]. GB 27999-2014; Beijing, China, Administration of Quality Supervision, Inspection and Quarantine of the P. R. China, 2014.
- [4] Edwards K D, Wagner R M, Briggs T, et al. Defining Engine Efficiency Limits[C]//. 17th DEER Conference. 2011: 3-6.
- [5] YAO Mingfa, ZHENG Zhaolei, LIU Haifeng. Progress and Recent Trends in Homogeneous Charge Compression Ignition (HCCI) Engines[J]. Progress in Energy and Combustion Science, 2009, 35(5):398-437.
- [6] Reitz R D. Directions in Internal Combustion Engine Research[J]. Combustion and Flame, 2013, 160(1):1-8.
- [7] Reitz R D, Duraisamy G. Review of High Efficiency and Clean Reactivity Controlled Compression Ignition (RCCI) Combustion in Internal Combustion Engines[J]. Progress in Energy and Combustion Science, 2014, 46:12-71.
- [8] Ma S, ZHENG Z, LIU H, et al. Experimental Investigation of the Effects of Diesel Injection Strategy on Gasoline/diesel Dual-fuel Combustion[J]. Applied Energy, 2013, 109:202-12.
- [9] Splitter D, Hanson R, Kokjohn S, et al. Reactivity Controlled Compression Ignition (RCCI) Heavy-duty Engine Operation at Mid-and High-loads with Conventional and Alternative Fuels[R]. SAE Paper 2010-01-0363, 2010.
- [10] Benajes J, Pastor JV, García A, et al. The Potential of RCCI Concept to Meet EURO VI NO_x Limitation and Ultra-low Soot Emissions in a Heavy-duty Engine Over the Whole Engine Map. Fuel, 2015, 159:952-61.
- [11] TONG, Laihui, LIU, Haifeng, ZHENG, Zunqing, et al. The Design and Optimized Combination of Combustion Modes over Full Load Range in a Multi-cylinder Light-duty Engine[R]. SAE Paper 2013-01-2623, 2013.
- [12] Pellegrini L, Marchionna M, Patrini R, et al. Combustion Behaviour and Emission Performance of Neat and Blended Polyoxymethylene Dimethyl Ethers in a Light-duty Diesel Engine[R]. SAE Paper 2012-01-1053, 2012.

[13] Pellegrini L, Marchionna M, Patrini R, et al. Emission Performance of Neat and Blended Polyoxymethylene Dimethyl Ethers in an Old Light-duty Diesel Car[R]. SAE Paper 2013-01-1035, 2013.

[14] LIU H, WANG Z, WANG J, et al. Performance, Combustion and Emission Characteristics of a Diesel Engine Fueled with Polyoxymethylene Dimethyl Ethers (PODE3-4)/diesel Blends[J]. Energy, 2015, 88:793-800.

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