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Full Length Article

The effects of DI fuel properties on the combustion and emissions characteristics of RCCI combustion

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ABSTRACT

An experimental investigation has been conducted to explore the effects of direct-injection (DI) fuel properties in dual-fuel reactivity-controlled compression ignition (RCCI) combustion on a single-cylinder, heavy-duty diesel engine. The combustion and emission characteristics of four DI fuels with cetane number (CN) ranging from 34 to 100 were compared under different combustion boundary conditions. The results showed that a higher CN DI fuel allows more advanced SOI timing, more EGR, and higher premixed ratio. However, although the operable DISOI timing and EGR regions can be extended, the operable Rp region is narrowed for higher CN fuels. In addition, there is a competing relationship between DI fuel CN and EGR/premixed ratio (Rp) in controlling CA50, PPRR, and HC/CO emissions. With late injection strategy, enlarging the reactivity gradient through increasing CN of DI fuel shows more promising effects on combustion rate and pressure rise rate reduction, which is desirable for high load extension. Comparing the highest indicated thermal efficiency (ITE) cases of different CN fuels, it's illustrated that the approach of lower EGR ($<$ 45%) with high Rp ($\sim$80%) is suitable for low CN fuel (i.e. CN34) with early injection strategy to obtain a lower PPRR and a better ITE simultaneously. However, at late injection condition, more EGR with lower Rp ($<$ 80%) is required to control NOx/soot emissions. For high CN fuel (CN $\geq$ 56), the approach of higher Rp ($>$ 80%) with high EGR ($\sim$45%) is suitable with either early or late injection strategy to simultaneously improve the PPRR, ITE and NOx/soot emissions.

1. Introduction

Reactivity controlled compression ignition (RCCI) is a potential low temperature combustion (LTC) concept to achieve clean and highly efficient combustion [1,2]. Within the RCCI mode, the port injection of low reactivity gasoline-like fuel with high research octane number (RON) to form a homogeneous charge is effective to suppress the auto-ignition, and the ignition events should be activated by the direct injection (DI) diesel-like fuel with high cetane number (CN). In this way, the overall fuel reactivity can be tuned to a particular level adapted to the operating condition. Furthermore, the direct injection yields mixture concentration and reactivity stratifications locally, which prevents the entire mixture from igniting instantaneously, thus results in more effective control over the ignition and combustion process compared to HCCI [3,4].

However, although RCCI has shown advantages compared to other combustion concepts, one of the potential issues for this concept is the high load extension, which is limited by the high pressure rise rate and high soot emission at high load conditions. According to Kokjohn et al.'s results derived from both optical diagnostic and simulations, it was found that within RCCI operation, mixture reactivity stratification plays dominant role in controlling the ignition and combustion events, followed by less but significant influence from mixture concentration stratification, and thermal stratification shows limited influence [3]. Therefore, much attention has been paid on the manipulation of reactivity and concentration stratification in this combustion mode.

One way to extend high load RCCI operation is injection strategy optimization to enhance the in-cylinder mixture stratification [5]. For example, it is well known that late injection could produce much stronger stratification attributed to reduced ignition delay. Ma et al. [6] showed that the high load limit could be extended to 1.39 MPa IMEP via an early 1st injection and a late 2nd strategy (2nd around −10–15 °crank angle (CA) after top dead center (ATDC)) in gasoline/diesel dual-fuel RCCI combustion. However, the high soot and NOx emissions with late injection limit further load extension.

Another effective approach to optimize the combustion and to extend the load limit is fuel property optimization to enlarge the reactivity gradient between the premixed and direct-injected (DI) fuels. It

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is seen that until now, the effect of fuel properties on dual-fuel combustion has been explored mainly on the low-reactivity components. Various low reactivity fuels, including natural gas [7–10], methanol [11–14], ethanol [15] and butanol [16–18] have been adopted in RCCI operation, and exhibit various advantages and disadvantages at different operating conditions [19]. These investigations demonstrated that higher octane number of port injected fuel shows remarkable influence on RCCI combustion, which is beneficial to extend the high load limit and improve the engine efficiency. However, although these high RON low reactivity fuels show privilege for high load extension, they are still facing various issues, such as high sensitivity to boundary conditions, high cycle to cycle variations, and high carbon monoxide (CO) and unburnt hydrocarbon (UHC) emissions, which still need further investigations [1]; whereas there were few reports about the dual fuel combustion investigation on the effects of the DI fuel properties. Therefore, it is desirable to further explore the effects of high reactivity fuels properties on RCCI combustion, emissions and load extension.

The high reactivity fuel in most of the previous RCCI works was diesel fuel. Another representative high reactivity fuel is bio-diesel, which has similar CN compared to diesel, with oxygen content to suppress soot formation and higher viscosity to create stronger concentration stratification. Successful RCCI operations have been conducted by Li et al. [20], Mohsin et al. [21] and Liu et al. [17]. To avoid the drawbacks of carrying two fuels, single fuel strategy can also be regarded as explorations on the effects of DI fuel properties in RCCI operation [22]. Small amount of cetane improvers, such as 2-EHN (2-ethylhexyl nitrate) and DTBP (di-tert-butyl peroxide) [11,23], were mixed with the single low reactivity fuel to improve the mixture reactivity, and then the mixture was directly injected into the cylinder, playing the role of high reactivity fuel. However, the controllability of combustion phasing by single fuel strategy is less effective than that of gasoline/diesel RCCI combustion due to the reduced stratifications in both reactivity and concentration [11,24,25].

Recently, the authors' group explored the utilization of a novel alternative fuel, polyoxymethylene dimethyl ethers (PODE) as the DI high reactivity fuel for RCCI operation [19]. PODE features high CN (> 75), high oxygen content (~47.95% wt.), low lower heating value (LHV) (21.77 MJ/kg) and unique molecular (no C–C bond), implying its potential for RCCI operation [26]. The results showed that stable RCCI operation is obtainable using PODE as the DI high reactivity fuel. The lower energy injection ratio (the fuel energy delivered by direct-injection per unit time) and high CN could significantly reduce the initial ignition energy, combined with its high oxygen content, both the peak pressure rise rate and soot emission can be effectively suppressed, thus much higher load can be obtained (1.76 MPa IMEP with PODE single injection vs 1.39 MPa IMEP with optimized diesel double-injection strategy). In the following study, the high load can be further extended up to 2.3 MPa IMEP with PODE and gasoline, which highlights the importance of DI fuel properties for combustion control [27].

Since these fuels may have different physical and chemical characteristics over a range of temperatures, it is of interest to understand the impact of these properties on the combustion event. Chuahy et al. explored the effects of the physical properties of the high reactivity fuel in a RCCI combustion strategy. It was found that the different boiling curves of the two fuels have minimal effect on the combustion phasing at early and late injection timing conditions [28]. Ickes et al. investigated the effect of CN on the combustion of gasoline-diesel dual fuel strategy on a six-cylinder heavy-duty diesel engine [29]. The results showed that low-cetane diesel fuel achieves a higher load conditions and a lower soot emission due to substantially longer ignition delay. In the range of high cetane number, further increased cetane number has little influence on dual-fuel combustion. However, in addition to CN, large differences in other fuel properties exist among these tested fuels, including the viscosity, volatility, low heating values, etc., thus it is difficult to solely reveal the role of CN on RCCI operation.

Based on these discussions, it's seen that the direct-injected (DI) fuel property has large influence on RCCI operation, but a thorough understanding on the effects of DI fuel properties on RCCI combustion and emission characteristics, especially the role of CN, is still not quite clear from the current literatures, and the influential factors of chemical composition and physical properties of DI fuels have not been eliminated yet. Therefore, the present study focuses on the effects of DI fuel properties, especially CN, on the combustion process under RCCI regime. Four DI fuels with different CN ranging from 34 to 100 were prepared and tested, and iso-octane was used as the low reactivity fuel. The combustion and emission characteristics of different DI fuels are compared under a load of about 0.97 MPa gross IMEP. The effects of premixed ratio, EGR and DISOI timing of various fuels on RCCI operation are also be compared and discussed. The objective of this work was to systematically explore the effects of the reactivity characteristics of the DI fuel in dual-fuel combustion strategies with different combustion boundary conditions. Cooperative control strategies in various boundary conditions were proposed to explore the approach to achieving high efficiency RCCI operation with different CN fuels. The current work aims to isolate the effects of the DI fuel CN characteristics in a general way, which can be helpful to guide future works on fuel research for advanced combustion strategies.

2. Experimental apparatus and procedures

The experiments were conducted on a modified six-cylinder heavy-duty diesel engine, wherein the sixth cylinder was separated from the other five for test purposes. This individual cylinder was equipped with independent port and DI fuel injection systems, intake temperature and pressure regulating systems, an EGR system, and so on. The schematic of the experimental setup is represented in Fig. 1, and the major engine specifications are summarized in Table 1. In order to operate in RCCI combustion mode, an electronically controlled port fuel injection (PFI) system was installed in the intake manifold to inject iso-octane. Direct fuel injection system was equipped with a common rail injection system and a conventional injector (Bosch) capable of a maximum injection pressure of 160 MPa. The rail-pressure, injection timing, and injection strategies could be adjusted by the self-developed calibration system flexibly. Details about this testbed can be found in the authors' previous studies [19,30].

The major instruments used for the in-cylinder pressure and emission measurements and their sensitivities and uncertainties are summarized in Table 2 [31,32]. All the measurements were carried out after attaining steady state for at least 2 min. The pressure data was taken with a resolution of 0.5 crank angle degree, and 100 consecutive engine cycles were acquired and averaged for each operating point. Major combustion characteristics, including the apparent heat release rate (AHRR), ignition delay (defined as the interval between start of injection and CA10, defined as the timing of 10% accumulated heat release), combustion phasing (CA50, defined as the timing of 50% accumulated heat release) and combustion duration (defined as the interval between CA10 and CA90), etc., all were calculated from the ensemble-averaged in-cylinder pressure by a combustion analysis software package. The EGR rate can be controlled by adjusting the exhaust backpressure valve and EGR valve. Under steady operating conditions, the EGR rate was determined through the ratio of CO_2 in intake to exhaust gas via the following formula Eq. (1), which were measured by an emission analyzer (HORIBA MEXA 7100DEGR):

$$\text{EGR ratio} = \frac{(CO_2\%)_{intake}}{(CO_2\%)_{exhaust}} \times 100\% \tag{1}$$

The combustion efficiency is calculated by the following formula Eq. (2):

$$\eta = 1 - \frac{\sum m_i Q_{LHV_i}}{\sum m_{fuel_i} Q_{fuel\text{-}LHV_i}} \tag{2}$$