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Multiple optical diagnostics on effect of fuel stratification degree on reactivity controlled compression ignition

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ABSTRACT

Reactivity controlled compression ignition (RCCI) was investigated on a light-duty optical engine under different fuel stratification degrees, using multiple laser diagnostic techniques. The engine was run at a speed of 1200 rpm and under a load of about 7 bar gross IMEP. To form different fuel stratification degrees, the direct-injection timings of n-heptane were changed, while the port-injection timings of iso-octane was kept constant. The fuel/air equivalence ratio and primary reference fuel (PRF) number were quantified by the fuel-tracer planar laser-induced fluorescence (PLIF) under non-combusting condition. The results indicated that with retarding n-heptane injection timing from −90° CA ATDC (RCCI-90 case) to −10°CA ATDC (RCCI-10 case), regions of higher fuel concentration and reactivity moved downstream to the edge of combustion chamber before high-temperature heat release (HTHR) phase. Time-resolved natural combustion luminosity imaging and single-shot OH PLIF imaging indicated that RCCI-10 case presented a staged combustion process that an auto-ignition first happened in the region of high reactivity around the combustion chamber and then another auto-ignition process took place in the region of low reactivity in the central part of the combustion chamber. The staged combustion feature involved in RCCI combustion could result in lower combustion pressure-rise rate. PLIF images of formaldehyde showed that formaldehyde first formed during low-temperature heat release (LTHR) phase in the regions where n-heptane resided. With retarding n-heptane injection timings, both formaldehyde and OH PLIF images presented more stratified distribution, and the consumption of formaldehyde and formation of OH processes got slower. OH PLIF images indicated that HTHR phase of RCCI could extend to the central part of combustion chamber. In the low-load LTC conceptual model proposed by Musculus et al. (2013), no HTHR happened and UHC formed in the central part of combustion chamber. This meant that RCCI could have less UHC emission than LTC in theory.

1. Introduction

Internal combustion engine is a vital prime mover for transportation, commerce and power generation in modern society. The huge number of vehicles and engines around the world consumes most of the crude oil and produces a large amount of pollutants emissions, like nitric oxides (NO_x) and soot. As one of the most extensively used internal combustion engines, the diesel engine has advantages in power output, fuel economy and durability [1]. In order to meet the strict emission regulations, diesel engines have been urged to reduce NO_x and soot emissions for decades. Several novel compression ignition strategies were proposed to achieve this end. These concepts can be termed as low-temperature combustion (LTC), which is a compromise between the well-known homogenous charge compression ignition (HCCI) and the traditional mixing-controlled diesel combustion [2,3]. Using diesel fuel, LTC has potential to operate the engine at low and medium engine load by the introduction of certain exhaust gas recirculation (EGR) [4,5]. However, it is difficult to extend diesel LTC operation to high or full engine load, because diesel fuel has low resistance to auto-ignition and too much EGR is required at these conditions to gain enough ignition delay for adequate fuel/air premixing. Excess EGR leads to combustion deterioration and fuel penalty [6–9]. This is mainly due to the high reactivity (cetane number) of diesel fuel. From the perspective of clean (low NO*x* and soot emissions) and efficient engine combustion, fuels of different reactivity are required under different operating conditions, i.e., a high cetane fuel at low load and a low cetane fuel at high load.

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To address this issue, Inagaki et al. [10] employed a dual-fuel (premixed iso-octane and direct injected diesel) compression ignition strategy, which was able to operate the engine up to 12 bar indicated mean effective pressure (IMEP) with ultra-low NO_x and soot emissions, using a reduced amount of EGR. This dual-fuel strategy was named as reactivity controlled compression ignition (RCCI) by Kokjohn et al. [11], since the desirable fuel reactivity could be modulated by blending two fuels of different reactivity according to operation conditions. RCCI was intensely investigated by engine bench tests [12–14] and results showed that RCCI could meet the current emissions regulations without relying on NO_x and soot after-treatment, and provided high thermal efficiency from light to mid-high engine loads. The peak gross indicated efficiency of gasoline/diesel RCCI was 56% at 9.3 bar IMEP [12], which is higher than the conventional diesel combustion and diesel LTC. However, at high or full engine load, excessive pressure rise rate (PRR) and soot emissions became the limiting factors to RCCI. A detailed understanding of the in-cylinder air-fuel mixture formation and combustion processes of RCCI is helpful to the further development of RCCI combustion strategies, and to the establishment of RCCI numerical calculation models. Thus, the optical diagnostics on the in-cylinder RCCI combustion process is necessary.

A series of optical diagnostics of RCCI were performed by coworkers from University of Wisconsin-Madison and Sandia National Laboratories [15,16]. Kokjohn et al. [16] studied the RCCI combustion process by high-speed imaging and planar fuel-tracer laser-induced fluorescence (PLIF) techniques. They found that the ignition sites first appeared in the downstream portion of the injected fuel jets, where the local fuel reactivity was high, and the rate of heat release could be controlled by fuel stratification. In a later work combined with chemical kinetics modeling [15], they tried to explain the role of equivalence ratio, temperature and fuel reactivity stratification for heat release rate control. It was concluded that the fuel reactivity was the dominant factor controlling ignition delay, followed by fuel concentration and temperature stratification. The combustion process of RCCI recorded by a high-speed camera was shown to be remarkably influenced by the fuel stratification degrees. However, the high-speed imaging is a line-of-sight technique, which shows the two-dimensional projection of the natural flame luminosity from the three dimensional reaction zones. Meanwhile it is unable to distinguish the low-temperature heat release (LTHR) phase and high-temperature heat release (HTHR) phase, respectively, which are very important features of RCCI combustion. PLIF imaging of formaldehyde and OH can provide valuable information of the two-phase ignition of RCCI. But few works have been concentrated on this issue, especially the RCCI combustion under different fuel stratification degrees. Besides, in the works of Kokjohn et al. [15,16], the engine load was confined to 4.2 bar gross IMEP due to limited optical engine strength. As mentioned above, the main challenge to RCCI operation comes from the excessive PRR and soot emissions at high engine loads, thus, optical diagnostics of RCCI combustion under a higher engine load has more practical significance.

In the present study, RCCI is investigated in a light-duty optical engine under a higher engine load of about 7 bar gross IMEP. Multiple optical diagnostics, including high-speed imaging, fuel-tracer PLIF imaging, and formaldehyde/OH PLIF imaging, were applied to evaluate the RCCI combustion process under different fuel stratification degrees. Iso-octane and n-heptane was used in the intake port injection (PI) and in-cylinder direct injection (DI), respectively. Different fuel stratification degrees were formed by varying the in-cylinder n-heptane DI timings while keeping the PI of iso-octane unchanged. The motivation of this paper is to gain insight into the in-cylinder combustion characteristics of RCCI under different fuel stratification degrees.

2. Experimental setup and optical diagnostic techniques

2.1. Optical engine system

A naturally aspirated, single cylinder optical engine was utilized in this investigation. The main engine specifications are listed in Table 1. A Bosch common-rail fuel injection system delivered n-heptane with pressure of 600 bar. Due to a two-valve configuration of the engine, the injector nozzle deviated a little from the center of the combustion chamber, as shown in Fig. 2. The injector nozzle had 6 holes with a diameter of 150 μm and a spray included angle of 150 degree. A commercial gasoline low pressure port fuel injector was installed in the intake port and iso-octane PI pressure was kept at 3 bar.

During the experiment, the electronic control unit (ECU) read the crank signal from engine, which was motored at a speed of 1200 revolution per minute (rpm) by a dynamometer, and produced a 10 Hz pulse to trigger a Nd: YAG laser (Pro-250, Spectra Physics) though the pulse delay generator (DG535, Stanford Research). When the fuel injection order was confirmed, ECU energized the injectors and trigged the intensified charge coupled device (ICCD) camera (DH734i-18F-03, Andor) through DG535. The DG535 synchronized of the timing sequence of signals among laser, ECU and camera.

To allow optical access through the bottom of the Bowditch piston in optical engine, a flat piston crown window was used, forming a cylindrical combustion chamber (diameter: 66 mm, height: 9.4 mm). A quartz ring window with a height of 36 mm, which was mounted at the top part of the cylinder wall, allowed horizontal laser sheets to enter the cylinder. In order to introduce the laser sheets into the combustion chamber around crank angles near top dead center (TDC), a cut-out of 40 mm was set on the right of combustion chamber. The above optical modifications of combustion chamber reduced the compression ratio to about 11.

Three laser beams (266 nm, 355 nm and 282.95 nm) were used separately for three different PLIF imaging techniques in this study. Each beam was formed into a 30 mm wide and less than 1 mm thick horizontal laser sheet by a group of cylindrical lens, and was directed horizontally into the cylinder though the quartz ring window. The relative position of cylinder head, extended piston and laser diagnostics region is shown at the top of Fig. 2. The horizontal laser sheet was maintained at a plane 10 mm below the firedeck. The distance between the firedeck and laser sheet is carefully chosen so that the laser sheet just passes through the main combustion regions. The PLIF signals were reflected by a 45° UV-mirror to an ICCD camera coupled with different fluorescence filters.

Table 1
Optical engine specifications.

Engine type	4 stroke
Bore	92 mm
Stroke	100 mm
Displacement	0.66 L
Connecting rod length	155 mm
Compression ratio	11
Combustion chamber shape	cylindrical
Combustion chamber diameter	63 mm
DI pressure	600 bar
Holes number of DI injector	6
Spray included angle of DI injector	150°
Injector hole diameter of DI injector	0.15 mm