

Simultaneous Measurement of Natural Flame Luminosity and Emission Spectra in a RCCI Engine under Different Fuel Stratification Degrees

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ABSTRACT

Reactivity controlled compression ignition (RCCI) is a potential combustion strategy to achieve high engine efficiency with ultra-low NO_x and soot emissions. Fuel stratification can be used to control the heat release rate of RCCI combustion. But the in-cylinder combustion process of the RCCI under different fuel stratification degrees has not been well understood, especially at a higher engine load. In this paper, simultaneous measurement of natural flame luminosity and emission spectra was carried out on a light-duty optical RCCI engine under different fuel stratification degrees. The engine was run at 1200 revolutions per minute under a load about 7 bar indicated mean effective pressure (IMEP). In order to form fuel stratification degrees from low to high, the common-rail injection timing of n-heptane was changed from -180° CA after top dead center (ATDC) to -10° CA ATDC, while the iso-octane delivered in the intake stroke was fixed. The natural luminosity imaging results indicated that, when n-heptane was injected at -180° ATDC, the combustion process looked like HCCI combustion at first with uniform blue flames all over the combustion chamber, but bright soot spots emerged later on. With retarding n-heptane injection timing, combustion regions with higher natural luminosity moved to the edge of the combustion chamber, and the natural flame luminosity got more stratified, showing more signs of soot radiation. The flame emission spectra from RCCI combustion under different fuel stratification degrees showed band spectra of OH, CH, CH_2O and C_2 , as well as continuous spectra of CO oxidation and soot radiation. Band spectra of OH, CH (431.4 nm) and C_2 (516.5 nm)/ CH_2O (422-424 nm and 434.5 nm) became more distinct and appeared successively with the retarding of n-heptane injection timing from -180° ATDC to -10° ATDC.

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INTRODUCTION

Diesel engine has superior efficiency due to a higher compression ratio and is widely used in modern society, but it has higher emissions of NO_x and soot because of the mixing-controlled combustion feature. In order to reduce the NO_x and soot emissions of diesel engine, several new combustion concepts were proposed. These concepts could be termed as LTC (low temperature combustion), an intermediate process between the well-known HCCI and conventional diesel mixing-controlled compression ignition. LTC introduced a considerable proportion of EGR (exhaust gas recirculation) to extend the ignition delay and to increase fuel/air premixing time. When the events of fuel-injection and ignition were temporally separated, fuel/air premixing time was sufficient to eliminated local fuel-rich regions and thus local combustion temperature. Consequently, both soot and NO_x emissions were reduced [1, 2].

However, LTC could only be limited to light and medium engine loads, because too much EGR was required to separate the fuel-injection and ignition events at mid-high engine load. The excessive EGR resulted in fuel penalty and a great rise of unburned hydrocarbons and CO emissions [3, 4]. This high demand for EGR could be ascribed to the high reactivity of the diesel fuel. From

perspective of the whole engine operation range, there is an optimal fuel-reactivity at a specified engine load, i.e., higher reactivity at light load and lower reactivity at high load [5].

Based on this view, reactivity controlled compression ignition (RCCI) was put forward [6, 7-8]. It delivered fuel of low reactivity, like gasoline, methane and alcohols, through intake port fuel-injection and fuel of high reactivity, like diesel, through in-cylinder injection. The ratio of these two fuels was adjusted according to engine loads. Extensive all-metal engine experimental researches showed that RCCI engine could gain quite high engine efficiency (with a peak gross indicated efficiency of 56% for gasoline/diesel RCCI operated at 9.3 bar IMEP [8]) with ultra-low soot/ NO_x emissions [9]. The operation range covered from light to mid-high load (2 bar IMEP to 14.6 IMEP for gasoline/diesel RCCI at 1300 rev/min [10]). One of the major obstacles for RCCI is further extension to high engine load, which is restricted by an excessive pressure rise rate and rising soot emissions [11]. Thus, further research about RCCI is still required, especially the understanding of the in-cylinder processes and characteristics for RCCI combustion at higher engine loads.

Kokjohn, et al. [12] studied the iso-octane/n-heptane RCCI combustion at a light load (4.2 bar IMEP) using fuel-tracer planar laser-induced fluorescence and high-speed imaging techniques. They found that the ignition kernels first formed in the downstream regions of high reactivity near squish region and then flames developed to low reactivity regions in the center of the combustion chamber. In a later work combined kinetic analysis [13], they further proved that fuel reactivity stratification played a major role in the ignition process of RCCI, followed by fuel concentration stratification and temperature stratification. Although these optical diagnostic studies provided great insights into the in-cylinder RCCI combustion processes, they were confined to relatively lower engine load. As mentioned before, the major challenge to RCCI comes from high engine load, where the pressure rise rate and soot emissions become main limiting factors. Thus, optical diagnostics on RCCI at a relatively higher engine load has more practical significance. In addition, natural flame emission spectra can be used to identify the intermediate chemical species taking part in the engine combustion process, which may be helpful to understand the characteristics of RCCI combustion. But few spectroscopic studies have been conducted on RCCI combustion under different fuel stratification degrees [14, 15, 16].

In the present work, the iso-octane/n-heptane RCCI combustion is studied at a relatively higher engine load of about 7 bar IMEP on an optical engine. The iso-octane delivered in the intake port was fixed, and the common-rail injection timing of n-heptane was varied from early to late, in the compression stroke, to form different fuel stratification degrees. Simultaneous measurement of natural flame luminosity and emission spectra of RCCI combustion was carried out under these fuel stratification cases. The aim of this work is to explore the combustion characteristics of RCCI under different fuel stratification degrees.

EXPERIMENTAL SETUP

The schematic of the optical engine system for simultaneous measurement of natural flame luminosity and emission spectra in RCCI combustion is shown in Figure 1. The optical engine was equipped with two fuel injectors, one low pressure injector in the intake port and one common-rail (CR) injector. Both of the fuel injectors were controlled by a fuel-injection system. During the operation of the engine test, electronic control unit (ECU) read the crank signal from the engine, which was run at 1200 rpm, and waited for the order from the fuel-injection control system. Once the fuel-injection order was confirmed, ECU sent two signals to energize the low-pressure injector in the intake port (not shown in Figure 1) and the CR injector. At the same time it sent another signal to the pulse delay generator (DG535, Stanford Research). Then the DG535 delayed the signal according to the interval between the start of fuel-injection and the crank angle for data acquisition, then triggered the ICCD (intensified charge coupled device) camera (DH734i-18F-03, Andor) for images acquisition and the fiber spectrometer (Bruker 250is) for spectra acquisition, respectively.

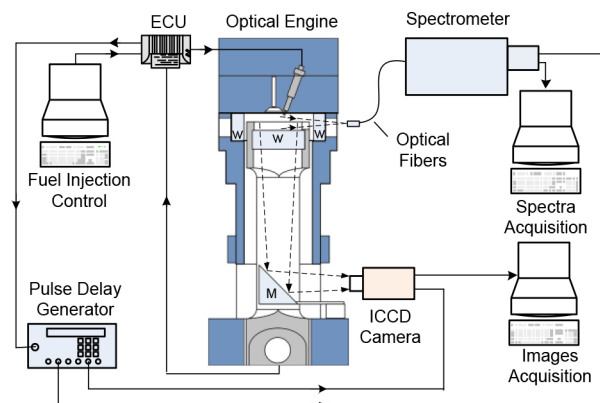


Figure 1. Schematic of the optical engine system for simultaneous measurement of natural flame luminosity and emission spectra. The signal flows between different devices are marked with arrows. W: quartz window, M: UV-mirror.

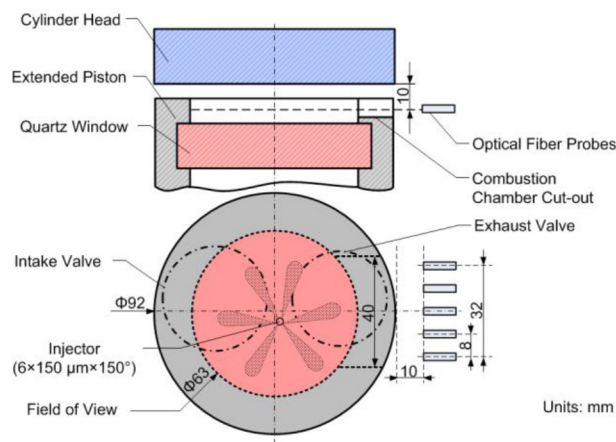


Figure 2. Structure and view field of the combustion chamber.

The optical engine was modified from a naturally aspirated, four-stroke, light-duty diesel engine (Bore $\times$ Stroke: 92 $\times$ 100 mm). The main engine specifications are shown in Table 1. The engine had a Bowditch-type extended piston with a cylindrical combustion chamber (diameter: 63 mm, height: 9 mm). The combustion chamber had a flat quartz window at the bottom. To implement laser-sheet diagnostic method (no laser used in the present study), a cut-out of 40 mm width was made on the right of combustion chamber, as shown in Figure 2. The compression ratio of the engine was reduced to about 11 after these optical modifications. An UV-mirror was set on the cylinder block below the extended piston. The natural flame luminosity in the combustion chamber was acquired through the bottom view field (diameter: 63 mm) of the piston. A quartz ring window with same inner diameter to cylinder block and of 35 mm height replaced part of the top cylinder liner. This made light signal detectable through the horizontal direction near the quartz ring. A fiber spectrometer was used to collect the flame emission spectra. Five optical fiber probes were fixed on the opposite of the combustion chamber cut-out on the right-hand side. The signals from these five detecting fiber probes were accumulated to give overall flame emission spectra. The position of these five optical-fiber probes is shown in Figure 2.

A Nikon UV-lens of 105 mm focal length was coupled to the ICCD camera and the maximum aperture of f/5.6 was chosen. The spectral response range of the ICCD camera is about 200~800 nm. The natural flame luminosity mentioned in the present study was composed of chemiluminescence and soot radiation. Another ICCD camera of the same type was coupled to the spectrometer to record the emission spectral. A 150 lines/mm grating with a spectral resolution of 3 nm was chosen for the spectrometer.

The signal delays set in DG535 for both ICCD camera and spectrometer were the same. And the gate-width (exposure time) of the ICCD camera and spectrometer were set as 139 μ s, which corresponded to one crank angle when the engine speed was 1200 rpm. This means that the natural flame luminosity captured by ICCD camera and emission spectra captured by spectrometer were from the same crank angle, i.e., simultaneous. The gain level of the ICCD camera and spectrometer were 100 and 50, respectively.

Table 1. Optical engine specifications

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
Holes number of CR injector	6
CR injector spray included angle	150°
CR injector hole diameter	0.15 mm

ENGINE OPERATION CONDITIONS

The engine was motored by a dynamometer at 1200 rpm. In order to reduce the risk of window failure caused by thermal and mechanical stresses and to extend the experimental period before window fouling, the engine was operated in a skip-fire mode that only one fuel-injection event (including port fuel injection and CR injection) was performed every other 20 cycles. The intake air was preheated to 75 °C to permit stable combustion due to the low compression ratio about 11. The engine was naturally aspirated and no EGR was introduced. The temperature of water coolant was kept at 95 °C during all tests.

Iso-octane of 70% by volume was injected with a pressure of 3 bar in the intake port, and the fuel-injection timing was fixed at -360° after compression top dead center. N-heptane of 30% by volume was delivered by the CR injector with a pressure of 600 bar, and the fuel injection timings were varied to form different fuel stratification degrees. The overall fuel/air equivalence ratio was about 0.77. The cases with n-heptane injected at -180°, -90°, -25°, and -10° ATDC are denoted as RCCI-180, RCCI-90, RCCI-25, and RCCI-10, respectively. The gross IMEP of these four cases are about 7 bar. The main operation conditions are summarized in Table 2.

Table 2. Engine operation conditions

	RCCI-180	RCCI-90	RCCI-25	RCCI-10
Engine speed (rpm)	1200	-	-	-
Intake pressure (bar)	1.01	-	-	-
Intake temperature (°C)	75	-	-	-
Port injection pressure (bar)	3	-	-	-
CR pressure (bar)	600	-	-	-
Ratio of iso-octane (% _v)	70	-	-	-
Ratio of n-heptane (% _v)	30	-	-	-
Port injection (°ATDC)	-360	-	-	-
Direct injection (°ATDC)	-180	-90	-25	-10
Overall equivalence ratio	0.77	-	-	-
Gross IMEP (bar)	7.0	7.0	6.8	6.9

“-”: same to the other cases.

“ATDC”: after compression top dead center

“%_v”: volume fraction

RESULTS AND DISCUSSION

Heat Release and Natural Flame Luminosity

Figure 3 shows the average cylinder pressures and heat release rates. All cases present a two-stage heat release process. The low temperature heat release (LTHR) stage is advanced with earlier n-heptane injection timing, but the high temperature heat release (HTHR) does not follow this rule. RCCI-25 has the most advanced HTHR and combustion phasing. Either earlier (RCCI-180/RCCI-90) or later (RCCI-10) n-heptane injection timing results in a retarded HTHR and combustion phasing. RCCI-180 has so early n-heptane injection timing that it presents a HCCI-like heat release feature. Although the engine load is relative high (7 bar IMEP), the pressure rise rate (PRR) for RCCI-180 is tolerable for the optical engine (8.3 bar/°CA) due to a lower compression ratio and the skip-fire operation mode. The PRR gets lower with retarding n-heptane injection timing. Late-injection strategy is often adopted to reduce PRR at higher engine load for RCCI in the literature, but soot/NO_x emission may become a problem with too late injection timing.

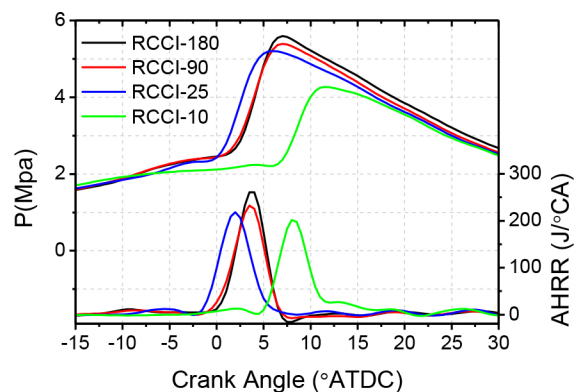


Figure 3. Average cylinder pressure and apparent heat release rate (AHRR) for RCCI-180, RCCI-90, RCCI-25 and RCCI-10.