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Study on ignition and flame development in gasoline partially premixed combustion using multiple optical diagnostics

Qinglong Tang[a], Haifeng Liu[a,*], Mingkun Li[a], Mingfa Yao[a], Zhongshan Li[b]

[a] State Key Laboratory of Engines, Tianjin University, Tianjin 300072, PR China
[b] Division of Combustion Physics, Lund University, P.O. Box 118, S22100 Lund, Sweden

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ABSTRACT

Gasoline partially premixed combustion (PPC) is a potential strategy to achieve high engine efficiency, as well as low NO_x and soot emissions. But the in-cylinder combustion process of PPC is not well understood. In this paper, multiple optical diagnostics are applied to investigate the PPC ignition and flame development in a light-duty optical engine under single-injection condition. For the injection timing of −25 CA after top dead center (ATDC), the results indicate that the combustion process of gasoline PPC can be basically divided into four stages: 1) multiple auto-ignition kernels emerging in fuel-rich regions; 2) flame front propagation of the ignition kernels towards fuel-lean regions; 3) auto-ignition in the end-gas of fuel-lean regions; 4) a “burnout” stage in the whole combustion chamber after the main heat release process ends. The natural flame emission spectra from these four stages in PPC are analyzed. Distinct flame front propagation is verified during the early stages of the flame development process by both formaldehyde and OH planar laser-induced fluorescence (PLIF) imaging. The wide spread and late persistence of OH radicals after the main heat release process may account for the low soot emissions of gasoline PPC. The flame expansion speeds, determined by monitoring the flame fronts extracted from the combustion images, are much higher than that in SI (spark ignition) or SACI (spark-assisted compression ignition) combustion. With earlier fuel injection timing of −90 CA ATDC, the flame propagation process is less pronounced, and the sequential auto-ignition process prevails. Variation of the fuel stratification degree caused by the different fuel injection timings is responsible for this transformation in the flame development pattern for gasoline PPC.

1. Introduction

The diesel engine is widely used in modern society due to its merits of superior reliability, engine power and fuel economy. However, a costly after-treatment system is required to curb its high emissions of soot and NO_x in order to meet stringent emissions regulations. To reduce the soot and NO_x emission of diesel engines, several novel compression ignition strategies have been proposed. These concepts can be classified as low temperature combustion (LTC), which is a compromise between homogenous charge compression ignition (HCCI) and traditional mixing-controlled diesel combustion [1]. One common trait of these concepts is the introduction of a considerable portion of exhaust gas recirculation (EGR), which is used to increase the ignition delay of diesel combustion. Consequently, these LTC concepts usually have a positive ignition dwell (the time from the end of fuel injection to ignition) [2]. The separation of the fuel injection and ignition process provides more time for fuel/air mixing, and the reduction of local fuel-rich zones in the combustion chamber leads to a lower peak combustion temperature. Accordingly, soot and NO_x emissions can drop simultaneously. These diesel LTC concepts are feasible at low and middle engine loads. however, when it comes to high engine load, too much EGR is required to attain adequate fuel premixing time, and the excess EGR results in the diminishment of combustion efficiency and a dramatic increase of unburned hydrocarbons (UHC) and CO [3,4]. In the work of Noehre et al. [4], at least a 70% percent EGR rate was required to separate the end of diesel fuel injection and start of combustion at a load of 15 bar gross IMEP (indicated mean effective pressure). This is ascribed to the high reactivity (cetane number, CN) of diesel fuel.

To alleviate the demand for EGR and gain longer ignition delays, fuels with lower CN are preferred. Johansson et al. [5] adopted a diesel fuel with CN of 21 to run an engine at about 16 bar net IMEP using only about a 50% EGR rate to gain a positive ignition dwell. Kalghatgi et al. [6,7] proposed a gasoline partially premixed compression ignition (gasoline PPC or PPC) strategy in which gasoline

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* Corresponding author.
E-mail address: haifengliu@tju.edu.cn (H. Liu).

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was directly injected in the cylinder of a diesel engine and ignited by compression. In this gasoline PPC concept, the advantage of the high resistance to ignition of gasoline is taken to gain higher ignition delays. It was indicated by Manente et al. [8,9] that PPC can be operated at loads as high as 25 bar gross IMEP with low emissions of soot and NO_x. In addition, a gross indicated engine efficiency of more than 50% could be achieved with acceptable maximum pressure rise rate by moderate EGR, tailored split injections and an optimized nozzle umbrella angle. The main challenges to PPC come from its poor combustion stability at low loads where the engine operating temperature is relatively low. There are several techniques to extend the lower load limit, such as negative valve overlap (NVO), rebreathing valve strategies and spark assistance [10,11].

Although PPC has been intensely studied in the all-metal test engines, most of the works reported in the literature only concern the engine performance and emissions. Knowledge of the in-cylinder combustion processes of PPC is still limited. Detailed optical diagnostics about fuel injection, mixture formation and combustion characteristics may help to promote better understanding of the combustion phenomena in PPC and provide experimental support for further simulation under PPC conditions.

Tanov et al. [12] explored the impact of split fuel injections on the combustion stratification by OH chemiluminescence imaging using PRF55 (mixture of 55% iso-octane and 45% n-heptane by volume). It was shown that combustion with a triple injection was more homogenous compared to single and double injections. Lu et al. [13] compared PRF70 and diesel split injection strategies by high speed imaging technique in an optical engine. They asserted that the evaporation process of PPC was faster than that of diesel operation and the combustion luminosity of diesel split injections was much higher than that of gasoline split injection strategies. Brands et al. [14] studied the effects of mixture stratification on PPC through variation of iso-octane injection timing from −100 to −300 CA ATDC with the NVO strategy. It was indicated that the auto-ignition event was initiated at multiple sites and then combustion progressed to new regions through sequential auto-ignition. But the sequential auto-ignition process occurred at a lower rate for the case of −100 CA than that of −300 CA.

The aforementioned works investigated the PPC process mainly through line-of-sight optical diagnostic technique of chemiluminescence imaging, which makes it hard to clarify the combustion characteristics of gasoline PPC. To gain further insight into the in-cylinder fuel/air mixing, ignition and flame development of gasoline PPC, multiple optical diagnostic techniques were implemented on an optical engine in this study. PRF70 was chosen as the low reactivity fuel. Fuel-tracer PLIF was utilized to determine fuel stratification before ignition. High-speed imaging, spectrometry, and formaldehyde/OH PLIF were applied to evaluate the combustion of PPC. The aim of the present work is to study the basic combustion behaviors, like ignition and flame development pattern, of gasoline PPC.

2. Experimental setup

2.1. Optical engine system

The experiment was carried out in a naturally aspirated, single-cylinder optical engine. The specifications of the engine are listed in Table 1. A Bowditch-piston was used, and a cylindrical combustion chamber (diameter: 66 mm, height: 9 mm) was designed with a flat quartz window at the bottom, allowing optical access to the combustion chamber through the piston. To permit the entrance of a laser sheet into the combustion chamber around the crank angle near TDC, a cut-out of 40 mm was set on the right of combustion chamber (see Fig. 2). Below the extended piston, an UV-enhanced reflection mirror was mounted on the cylinder block. A quartz ring window replaced a part of the top cylinder liner, making the upper part of cylinder visible from the horizontal direction and passable for the laser sheet. The combustion chamber modifications reduced the compression ratio to about 11.

Table. 1
Optical engine specifications.

Bore	92 mm
Stroke	100 mm
Displacement	0.664 L
Connecting rod length	155 mm
Compression ratio	11
Combustion chamber shape	cylindrical
Combustion chamber diameter	63 mm
Common rail pressure	600 bar
Holes number of injector	6
Spray included angle	150°
Injector hole diameter	0.15 mm

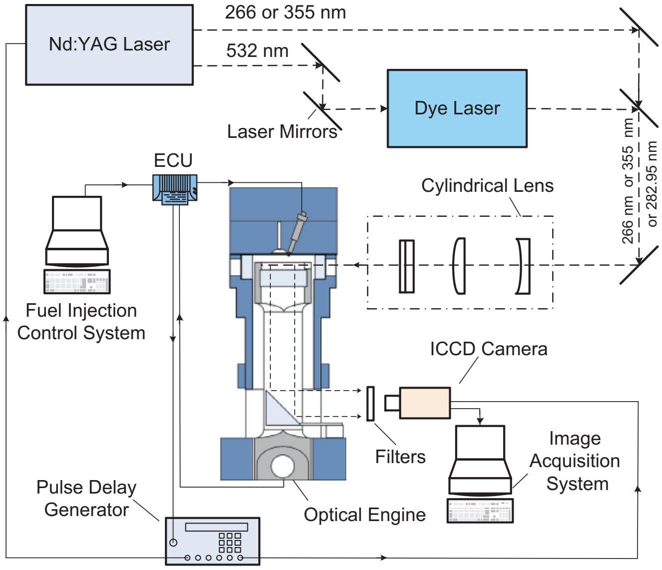

Fig. 1. Schematic of the laser diagnostic systems for the optical engine. The 266 nm, 355 nm and 282.95 nm lasers were used separately, to stimulate the fluorescence from fuel-tracer (toluene), formaldehyde and OH, respectively.

As illustrated in Fig. 1, during the experiment, the electronic control unit (ECU) read the crank signal from the engine run at 1200 rpm (revolutions per minute) and produced a pulse of 10 Hz to trigger a Nd:YAG laser (Pro-250, Spectra Physics) though a pulse delay generator (DG535, Stanford Research). The ECU waited for the fuel injection order from the fuel injection control system, and when the order was confirmed, the ECU sent a signal to energize the injector and at the same time trigged the ICCD camera (DH734i-18F-03, Andor) through the DG535. The timing sequence of these signals was synchronized by the DG535.

The fuel injection was controlled by a Bosch common rail system. Due to the 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 266 nm, 355 nm and 282.95 nm lasers were used separately, to stimulate the fluorescence from fuel-tracer (toluene), formaldehyde and OH, respectively. Each laser beam was formed into a thin horizontal laser sheet less than 1 mm with 30 mm wide by a cylindrical lens group and directed into the cylinder though the quartz ring window. The horizontal laser sheet was located in the plane 10 mm below the firedeck. The geometric structure of the combustion chamber and the field of view for