

# Study on the Double Injection Strategy of Gasoline Partially Premixed Combustion under a Light-Duty Optical Engine

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## ABSTRACT

Gasoline partially premixed combustion (PPC) is a potential combustion concept to achieve high engine efficiency as well as low NO<sub>x</sub> and soot emissions. But the in-cylinder process of PPC is not well understood. In the present study, the double injection strategy of PPC was investigated on a light-duty optical engine. The fuel/air mixing and combustion process of PPC was evaluated by fuel-tracer planar laser-induced fluorescence (PLIF) and high-speed natural luminosity imaging technique, respectively. Combustion emission spectra of typical double injection case were analyzed. The primary reference fuel, PRF70 (70% iso-octane and 30% n-heptane by volume) was chosen as the lower reactivity fuel like gasoline. Double injection strategies of different first fuel injection timing and mass ratio of the two fuel injections were comparatively studied. The results indicated that the combustion process of PPC was initiated by multipoint auto-ignition and these ignition kernels lied in the position where local equivalence ratio was relatively high. Then the flame fronts of these ignition kernels expanded to the region with lower fuel concentration. Jet/wall interaction, which hindered the fuel/air mixing of the first early fuel injection, was proved to have significant impact on the double injection PPC under low engine load. With an earlier first fuel injection timing and suitable mass ratio of the two fuel injections, the adverse impact of jet/wall interaction on fuel/air mixing could be reduced.

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## INTRODUCTION

Recently, several novel compression ignition strategies were proposed to reduce the soot and NO<sub>x</sub> emission of the diesel engines. These concepts could be termed as low temperature combustion (LTC), which was a compromise between well-known homogenous charge compression ignition (HCCI) and the traditional mixing-controlled diesel combustion (CI) [1, 2]. These concepts were characterized by the introduction of a considerable portion of exhaust gas recirculation (EGR) to increase the ignition delay of diesel combustion. And the fuel injection process and ignition process were often separated, i.e. a positive ignition dwell, which is the time from the end of fuel injection and to the beginning of ignition, was obtained [3]. This separation between the fuel injection and ignition process offered sufficient time for fuel-air mixing. As a consequence, the emission of soot and NO<sub>x</sub> were simultaneously reduced due to the leaner local charge equivalence ratio and the lower local peak combustion temperature, respectively. It was feasible to run the engine at low and middle loads with diesel LTC strategy. But at high loads, too much EGR was required to gain a positive ignition dwell, and the excess EGR resulted in lower combustion efficiency and great increase of unburned hydrocarbon and CO [4, 5]. The high reactivity (cetane number, CN) of diesel fuel was responsible to this dilemma. From the perspective of fuel reactivity, fuel with lower CN was preferred to alleviate the demand for EGR to obtain longer ignition delay at high engine load.

Johansson et al. [6] employed fuel with CN of 21 to get a positive ignition dwell using only about 50% percent EGR rate to operate the engine at about 16 bar net IMEP, and the soot and NO<sub>x</sub> emissions were low. By comparison in the work of Noehre et al [4], at least 70% percent of EGR was required to achieving this end using pure diesel at a load of 15 bar gross IMEP. Later, Kalghatgi et al. [7, 8] proposed a gasoline partially premixed compression ignition (PPC) strategy, in which gasoline was used as fuel in compression ignition engines. In this PPC concept, the advantage of high resistance to ignition of gasoline is taken to gain higher ignition delay. Manente et al. [9, 10] concluded that PPC can be operated at loads as high as 25 bar gross IMEP with low emissions of soot and NO<sub>x</sub>. And a gross indicated engine efficiency of more than 50% could be achieved with acceptable maximum pressure rise rate by moderate EGR and tailored multiple injections strategy. The PPC strategy had advantages in the high engine load, but when it came to low load, where the intake boost pressure and engine operation temperature were relatively low, the combustion stability turned to be a great challenge to PPC strategy due to the lower reactivity of gasoline. Several techniques, such as negative valve overlap (NVO), rebreathing valve strategy and spark plug assistance, were applied to extend the lower load limit [11, 12].

The investigations on gasoline PPC under all-metal engine test bench were intense and mainly concerned the engine performance and emission. But few works were concentrated on the in-cylinder process of PPC, like fuel injection, mixture formation and combustion characteristics. Double injection strategy was often adopted in the PPC concept. The first fuel injection formed premixed charge and the second fuel injection, which produced large fuel stratification, triggered the ignition process. Compare to single fuel injection, the double injection strategy could reduce the soot emissions and also helped in moderating maximum pressure rise rate and lowering cyclic variation at high loads [7]. Tanov et al. [13] studied the degree of stratification for gasoline PPC under low load ( $\lambda=3.5$ ) engine conditions using multiple injection strategy. The intake air preheating and NVO were employed to permit the stable engine operation at low load. Primary Reference Fuel with 55% iso-octane and 45% n-heptane (PRF55) was used to represent the gasoline, partially due to the lower compression ratio of 11.3. OH chemiluminescence imaging from PPC combustion analyses showed that combustion with triple injection was more homogenous compared to single and double injection. Lu et al. [14] conducted the PPC operation fueled with PRF70 fuel at low load ( $\lambda=2.3$ ) condition on a light-duty optical engine. Double injections of two fuel distribution strategies (50:50 and 70:30) were studied and the combustion processes of double injection strategy of PRF70 and diesel were compared by high-speed imaging technique. It was indicated that the 50:50 double injection strategy produced less soot emissions than the 70:30 strategy and the combustion efficiency of PPC got promoted with the advancing of the first fuel injection timing. The combustion luminosity of PRF70 double injection was much lower than that of diesel double injection.

The PPC investigations carried out on optical engine as mentioned above were often confined at very low load due to the limited strength of optical engine. For example, the IMEP of most test cases from Lu et al. [14] was less than 3 bar. At this low load, the combustion and thermal efficiency of the engine was quite low, and the engine cyclical variation is high. To probe the in-cylinder process of PPC with double injection strategy at higher engine load, further research is necessary.

In this paper, the double injection strategies of different first fuel injection timing from  $-50^\circ$  to  $-70^\circ$  and mass ratio of the first and second fuel injections from 0 to 100% was comparatively studied at a higher engine load of about 6 bar net IMEP. Fuel-tracer PLIF is a laser-based technique that is widely used to quantify the fuel/air equivalence ratio [15, 16]. To get the overall fuel stratification and learn the role it plays in the ignition and flame development of PPC, fuel-tracer LIF technique was implemented in this study. PRF70 fuel and toluene were chosen as fuel and tracer, respectively. High-speed imaging technique was introduced to record the liquid-phase fuel injection and combustion process, and the natural combustion emission spectra of typical double injection case were acquired and analyzed. The main purpose of this study is to gain insight into the in-cylinder fuel/air mixing and combustion process of gasoline PPC with double injection strategy.

## EXPERIMENTAL SETUP

### Optical Engine

The optical engine was modified from a naturally aspirated, single cylinder, light-duty diesel engine (Bore  $\times$  Stroke: 92 $\times$ 100 mm). The specifications of the optical engine are listed in Table 1. The piston was Bowditch-type with a cylindrical combustion chamber (diameter: 66 mm, height: 9 mm) which had a flat quartz window at the bottom. To permit the entrance of laser sheet to the combustion chamber around the crank angle near TDC, a cut-out of 40 mm width was set on the right of combustion chamber (see Figure 2). The compression ratio of the engine was reduced to 11 after these optical modifications. A UV-mirror was mounted on the cylinder block below the extended 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 laser sheet or other light source accessible to the combustion chamber through the cut-out from the horizontal direction.

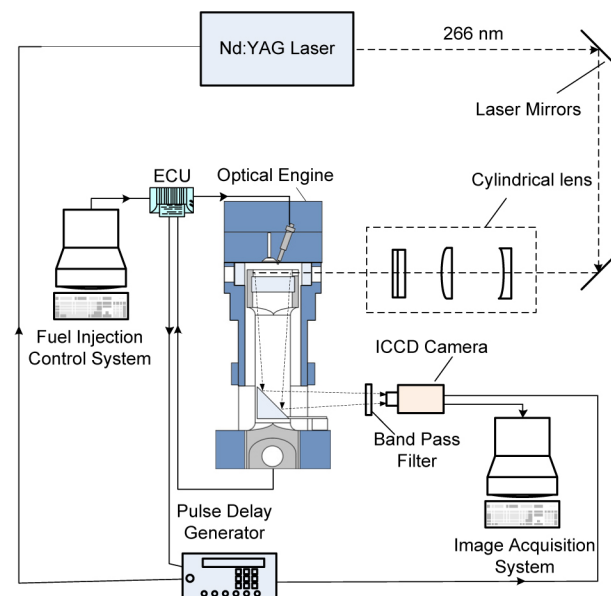


Figure 1. Schematic of the fuel-tracer PLIF system.

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       |
| Holes number of injector    | 6           |
| Spray included angle        | 150°        |
| Injector hole diameter      | 0.15 mm     |

The schematic of the fuel-tracer PLIF system for optical engine is shown in Figure 1. During the actual operation of the fuel-tracer LIF test, the electronic control unit (ECU) read the crank signal from the engine run at 1200 revolutions per minute and produced a 10 Hz pulse to trigger a Nd:YAG laser (Pro-250, Spectra Physics) through the pulse delay generator (DG535, Stanford Research). Meanwhile, the ECU waited for the fuel injection order from the fuel injection control system. When the order was confirmed, ECU sent a signal to energize the injector and at the same time triggered the ICCD camera (DH734i-18F-03, Andor) after certain interval set by DG535. The timing sequence of these signals was synchronized by DG535. When the high-speed imaging of the combustion process was conducted, the laser was shut down and the ICCD camera was replaced by the high-speed camera.

A Bosch common rail system controlled the fuel delivery into the cylinder. The injector had 6 holes of 0.15 mm diameter and the spray included angle was 150 degree. As shown in Figure 2, due to the two valve configuration of the engine, the injector nozzle deviated a little from the center of the combustion chamber.

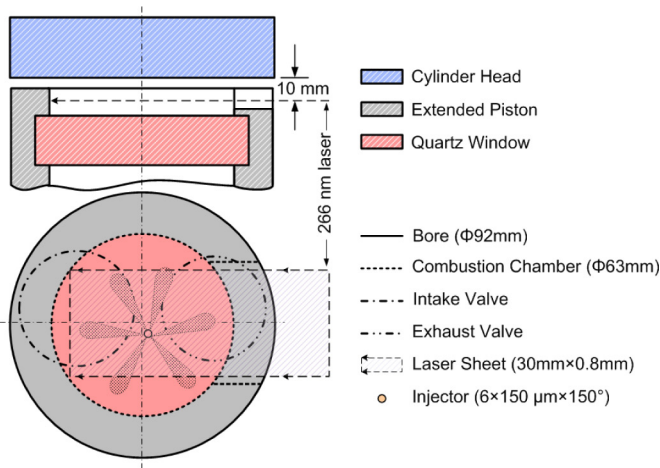


Figure 2. Structure and view field of the combustion chamber.

### Optical Diagnostic Techniques

For fuel-tracer PLIF technique, the fourth harmonic (266 nm, 60 mJ per pulse) of the Nd:YAG laser was used to stimulate the tracer fluorescence of toluene. The laser beam was formed into a thin sheet less than 1 mm and 30 mm wide horizontal laser sheet by a cylindrical lens group and directed into the cylinder through the quartz ring window. The horizontal laser sheet was located 10 mm below the firedeck. The geometric structure of the combustion chamber and field of view for optical diagnostics are shown in Figure 2.

Before the implementation of tracer-PLIF test in optical engine, the laser-induced fluorescence spectra of the fuel (99%<sub>v</sub> PRF70 + 1%<sub>v</sub> toluene) used in engine test was acquired by a spectrometer coupled with or without a band pass fluorescence filter. The 266 nm laser of 10 mJ per pulse was used to stimulate the fuel held in a quartz cuvette. The result is presented in Figure 3. Without filtering, remarkable laser scattering is witnessed at 266 nm and the main fluorescence spectra is around 270-340 nm. By using a 292 nm band pass filter (Semrock, FF01-292/27), whose transmission rate curve is presented in Figure

3, the laser scattering is eliminated. So in the engine test, the filter was coupled to the ICCD camera to capture the PLIF signal from toluene tracer.

During the fuel-tracer PLIF engine test, the intake air was replaced by pure N<sub>2</sub> to eliminate the O<sub>2</sub> quenching effect to the fluorescence signal. The fluorescence signal in the laser-sheet diagnostic region was reflected by the mirror and captured by the ICCD camera, equipped with a Nikon UV-lens of 105 mm focal length and the fluorescence filter. For time sequence, the laser pulse was bracketed with the ICCD gate width of 50 ns with the beginning of gate width aligned to the onset of laser pulse, and the gain level of ICCD was set to 200. The image acquisition rate of the ICCD camera is low and the laser pulse is fixed at 10 Hz, hence only one frame image could be acquired in one engine cycle.

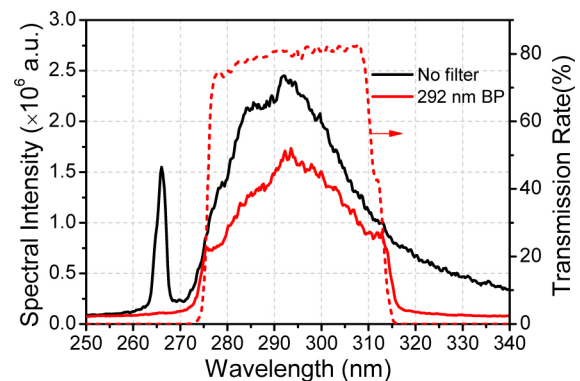


Figure 3. Laser-induced fluorescence spectra of the fuel-tracer mixture (99%<sub>v</sub> PRF70 + 1%<sub>v</sub> toluene) in a cuvette stimulated by 266 nm laser when the spectrometer is coupled with and without 292 nm band pass (BP) filter, and the transmission rate curve of the BP filter.

An in-situ calibration process was done to quantify of charge equivalence ratio by the method proposed by Musculus et al. [17] and Kokjohn et al [18]. The principal of the calibration process is that the PLIF signal per mole molecule is the function of averaged cylinder temperature and pressure at specified crank angle. If we want to determine the equivalence ratio at a certain crank angle after the 2-D LIF image is acquired, we need to know the relative fluorescence per illuminated molecule at this crank angle. To get the relative fluorescence per illuminated molecule at the image acquisition crank angle, 26 mg fuel was injected early in the intake stroke to form a uniform distribution at the actual LIF acquisition crank angles. To correct the influence of local temperature non-uniformity, which was caused by fuel concentration stratification, on the fluorescence intensity, an iteration procedure was performed to account for the fuel evaporation cooling effect at each pixel assuming isenthalpic fuel vaporization. Details of this calibration method can be found in [18,19].

For the combustion process imaging, a high-speed camera (Photron SA1) was used to record the fuel injection and subsequent combustion process. A Nikon lens of 50 mm focal length was coupled to the camera. The high-speed camera has no signal intensifier, so the largest aperture F1.4 was chosen to visualize the initial ignition kernels of PPC. The frame rate and exposure time of camera were set