

Characteristics of High Pressure Jets for Direct Injection Gas Engine

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ABSTRACT

The direct injection (DI) natural gas engine is considered as one of the promising technologies to achieve the continuing goals of the higher efficiency and reduced emissions for internal combustion engines. Shock wave phenomena can easily occur near the nozzle exit when high pressure gaseous fuel is injected directly into the engine cylinder. In the present study, high pressure gas issuing from a prototype gas injector was experimentally studied using planar laser-induced fluorescence (PLIF) technique. Acetone was selected as a fuel tracer. The effects of injection pressures on the flow structure and turbulent mixing were investigated based on a series of high resolution images. The jet macroscopic structures, such as jet penetration, cone angle and jet volume, are analyzed under different injection pressures. Results show that barrel shock waves can significantly influence the jet flow structure and turbulent mixing. With the increase of injection pressure, the jet cone angle and jet volume are obviously increased due to the strong expansion of barrel shock waves. This would be helpful to enhance the fuel-air mixing rate.

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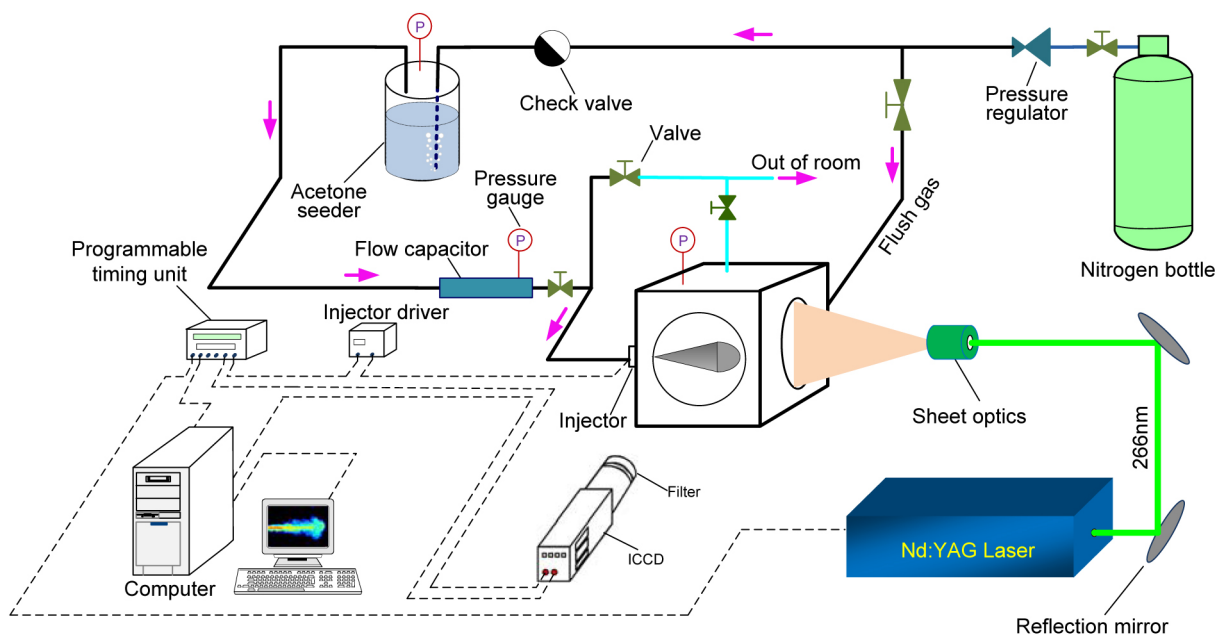
INTRODUCTION

Natural gas (NG) is considered as a promising alternative fuel for internal combustion engines to meet stringent emission regulations. NG has a high octane number and therefore it is quite suitable for diesel engine with relatively high compression ratio (CR). Nonetheless, NG cannot be used in compress ignition engines alone due to its high spontaneous ignition temperature. Currently, a popular way to apply natural gas into diesel engines is dual-fuel combustion mode. As the primary fuel, compressed natural gas (CNG) is admitted into the intake manifold and then mixed with air in the manifold and the cylinder. After that, the homogenous fuel (NG)-air combustible mixture is ignited by a small amount of high cetane number pilot fuel (e.g. diesel) near the top dead center. This kind of dual-fuel combustion CNG engine is a promising technique for controlling both NO_x and soot emissions even on existing diesel engines with slight modification to the engine structure [1].

However, there are several drawbacks in terms of engine performance when the diesel engine is operated with the premixed CNG-air mixture. During the low load and part load conditions, a reduction of the air supply is necessary to avoid too lean fuel-air mixture in the combustion chamber. As a consequence, the output power and engine efficiency are

decreased resulting from the low mean effective pressure of the engine. Therefore, dual-fuel engines should not be throttled/controlled on the air side [1]. In addition, high intake air pumping losses can be caused by the need to throttle the intake air flow rate at part load engine operation conditions. On the other hand, unburned hydrocarbon (HC) emissions which is consistent with the quality of the combustion process of the engine is considerably higher compared to the ones under normal diesel operation, in particular at the lower load conditions [2]. As widely recognized, this is due to the lower charge temperature and fuel-air ratio, resulting in a slower combustion rate and allowing small quantities of unburned fuel-air mixture to escape from combustion process [1, 2, 3]. Furthermore, for the premixed fuel-air mixture combustion engine, the "methane slip", such as the filling of the crevice volumes with unburned fuel-air mixture and fuel short-circuit from inlet to exhaust pipe is also considered as very important sources dominating the formation of HC emissions.

In order to further improve the performance of dual-fuel CNG engines, CNG direct-injection (DI), stratified charge, pilot ignition strategy has been attracted by more and more CNG engine researchers and manufactures in recent years. For this kind of technology, the proper distribution of the fuel-air combustible mixture in the combustion chamber is



(a) Schematic diagram of experimental setup

Fig. 1. Experimental set-up and gas injector

critically important for the ignition performance, which significantly influences the combustion process [4]. Therefore, it is very necessary to gain an in-depth understanding of jet structure and mixing process prior to the combustion process.

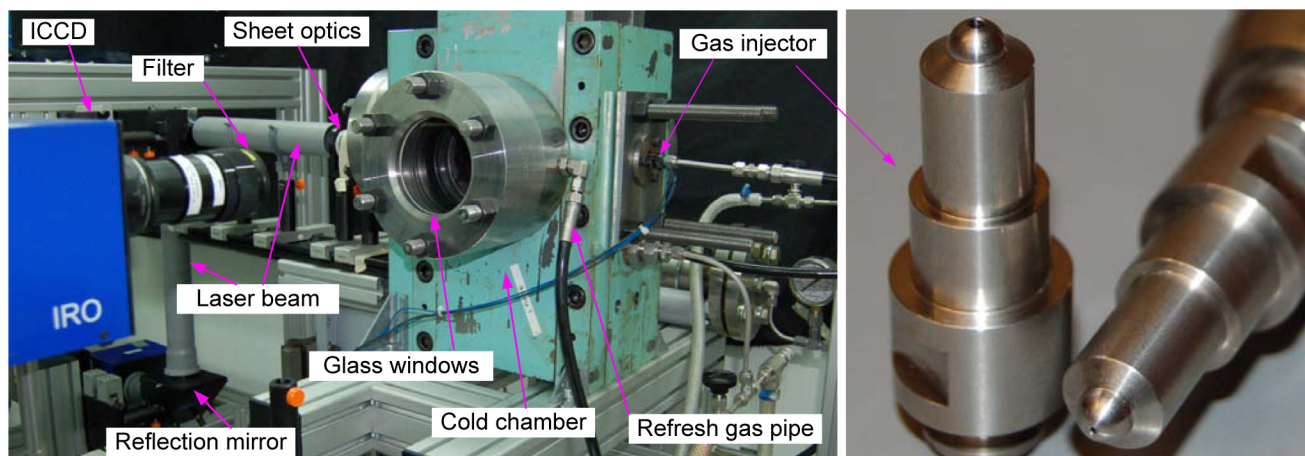
In general, for liquid fuel fueled engines, higher injection pressure can significantly improve the atomization and enhance the air-entrainment. As a consequence, the soot formation is substantially reduced resulting from a leaner mixture in the spray cone. For DI gas engine, injection pressure (gaseous fuel) also plays an important role for the engine performance. McTaggart-Cowan et al. [5, 6] investigated the effects of the gas injection pressure on a compression-ignition DI-CNG dual-fuel model engine. Based on the results of the engine performance, they found that higher injection pressures reduce the soot emissions in mid load and high load operating conditions.

However, the characteristics of high pressure gaseous fuel jets are still not understood well. Only a few studies have provided detailed information on high pressure pulsed jets in the gas engine research field. Hill et al. [7] investigated the effects of injection pressure ratio on the penetration in a fixed volume chamber using Schlieren technique, and developed an analytical relationship for penetration based on self-similar characteristics of transient turbulent jets. Rubas et al. [8] examined the natural gas direct injection and mixing in an optical engine using planar laser-induced fluorescence (PLIF) technique. The injection pressure was 180bar and cylinder pressure as high as 20bar was used to match the in-cylinder density during the injection in a firing engine. Recently, Salazar et al. [9, 10] also used PLIF technique to study the mixing process in an optically accessible DI hydrogen engine

with high pressure injection (80-116 bar). They found that both the tumble flow and nozzle designs can influence the mixture formation and distribution. Baert et al. [11] visualized the transient jets using planar laser sheet Mie scattering (PLMS) and measured the jet flow field using particle image velocimetry (PIV). The jet penetration and jet angle were investigated under different injection pressure ratios (15-40 bar). Most recently, the effects of injection pressure on the mixture formation were also reported by Roy et al. [12] and Bruneaux et al. [13] using different optical techniques. Nearly all of the previous studies only focused on the jet macroscopic characteristics (e.g., jet penetration and jet cone angle), and did not mention or give detailed information of the effects of shock waves on the mixture formation. Actually, the flow in the near-field region can significantly influence the downstream flow structures and turbulent mixing, in particular for the underexpanded jet, since the jet angle can be increased by the expansion shock waves, but also the jet turbulent can be enhanced by the shock-induced instability. Therefore, the detailed information of the near-field region is very important to fully understand jet mixing in a DI gas engine.

EXPERIMENTAL SET-UP

The high pressure ratio gas jet measurement using PLIF technology is shown in Fig.1. For safety reasons, compressed nitrogen was used instead of high pressure natural gas. An accumulator was connected with the injector to weaken the fluctuation of injection pressure during the test. The injection pressure can be flexibly controlled and adjusted by a pressure regulator near the high-pressure nitrogen bottle. The



(b) Photograph of the experimental setup and the gas injector tip ($D=1.4$ mm)

Fig. 1 (cont). Experimental set-up and gas injector

photograph of the experimental setup and the gas injector are shown in Fig. 2. The solenoid valve gas injector has a single straight nozzle hole. In this work, the diameter of the nozzle hole was $D = 1.4$ mm, and the jet pressure ratio (JPR) was from 10 up to 40. The injection duration was $t_d = 4.0$ ms. More detailed information about the experimental set-up and PLIF system used in the present study has already been described thoroughly elsewhere [4, 14, 15].

RESULTS AND DISCUSSION

As a non-intrusive and non-particle seeding laser diagnostic technique, PLIF has ability to capture the inner structure of high-pressure pulsed jets. The results and observation provide a necessary understanding of the shock waves effect on jet structure and the mixing process.

Visualization of the Jet Structure

As mentioned in our previous work [4], the flow pattern of a jet issuing from a nozzle depends primarily on the ratio of the nozzle exit pressure to the ambient pressure (P_e/P_∞) and the ratio of the upstream fuel-supply pressure to the ambient pressure (P_0/P_∞). According to these pressure ratios, the free jet may have three patterns: subsonic, moderately underexpanded and highly underexpanded. Figure 2 shows the evolution of the jet structure in the beginning of the jet. Obviously, the jet displays the different structure under different JPRs. This is due to that the different JPRs leads to different (P_e/P_∞) and (P_0/P_∞) at different injection times. The shock structures (diamonds shock or barrel shock) become clear with the increase of JPRs. These shock waves could be considered as one of the main perturbation sources for the turbulence [14], which would play an important role in both the gas/air mixing process and the jet macrostructure. The quantitative study of the jet structure will be given in the following sections.

Figure 3 shows the jet structure in the fully developed stage under different JPRs. when the jet fully is developed, P_e/P_∞ and P_0/P_∞ are increased highly enough, and the jet becomes highly under expanded. Hence, the barrel shock structures are clearly visible in the near-field region of the jet. Meanwhile, the turbulent structure seems more and more intense. One important reason is that shock-induced turbulence is increased with the increase of JPR. These turbulent structures are very important for the enhancement of the gas jet mixing.

Definitions of the Jet Macroscopic Structure

Macroscopic structures, such as the jet area (or volume), the jet penetration and the jet cone angle, are concerned as the most important parameters to influence the mixture formation for DI engines. This section will focus on the macroscopic structures of pulsed gas jets. In general, the jet sides may be much unpredicted variations due to the turbulence and vortex structures, which usually bring a big challenge to accurately analyze the jet structures. Threshold intensity is usually used as one effective method to analyze the macroscopic structures of jets and sprays based on the digitized images. The intensity threshold level is usually flexible according to the optical measurement methods and the background and image signal levels. Hentschel et al [16] have used 10% threshold level for the gasoline spray images based on Mie-scattering and PLIF techniques, while Naber et al. [17] and Baert et al. [11] even have selected 50% threshold level for their spray and jet digitalized images. However, too high threshold level may lead to the information lost. In the present study, the macroscopic structures are analyzed based on 5% threshold of time-averaged image, since the high quality PLIF image with little noise can be acquired after data reduction procedure, as shown in Fig. 4.