

An Experimental Study on Diesel Spray Injection into a Non-Quiescent Chamber

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ABSTRACT

Visualization of single-hole nozzles into quiescent ambient has been used extensively in the literature to characterize spray mixing and combustion. However in-cylinder flow may have some meaningful impact on the spray evolution. In the present work, visualization of direct diesel injection spray under both non-reacting and reacting operating conditions was conducted in an optically accessible two-stroke engine equipped with a single-hole injector. Two different high-speed imaging techniques, Schlieren and UV-Light Absorption, were applied here to quantify vapor penetration for non-reacting spray. Meanwhile, Mie-scattering was used to measure the liquid length. As for reacting conditions, Schlieren and OH* chemiluminescence were simultaneously applied to obtain the spray tip penetration and flame lift-off length under the same TDC density and temperature. Additionally, PIV was used to characterize in-cylinder flow motion. Results were compared with those from the Engine Combustion Network database obtained under quiescent ambient conditions in a high pressure high temperature vessel. Because of the air flow induced by piston movement, in-cylinder conditions in the two-stroke engine during the spray injection are highly unsteady, which has a significant impact on the spray development and interference on the spray visualization. From the comparison with quiescent data from the Engine Combustion Network, air flow induced by piston movement was found to slow down tip penetration. Moreover, both ignition delay and lift-off length under unsteady flow conditions show less sensitivity with ambient temperature than that of quasi-steady conditions.

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INTRODUCTION

Fuel-air mixing plays a significant role in combustion and emission process in diesel engine. Better understanding on the effect of different operating conditions on the mixing between spray and ambient gas will help improve the efficiency and meet the increasingly stringent emission regulations.

For the last decades, thanks to the development of all kinds of optical techniques, many investigations have been done to study some quantitative spray and flame parameters during the fuel-air

mixing and combustion process. Injection usually takes place into a high pressure high temperature vessel at constant volume or pressure, where the air-flow velocity is quite low compared with that of the injected spray, so the ambient conditions can be considered as quiescent. Plenty of experiments are available in the literature either from constant-volume vessels or constant pressure ones. Detailed analysis on the effects of different operating conditions (gas density, ambient temperature, oxygen concentration) and injection pressure on the vapor penetration[1,2], liquid length[3,4], flame lift-off length[5,6], ignition delay[7,8] or even

reacting spray dynamics have been investigated [9, 10, 11]. Thanks to these efforts, the mechanism of the mixing and combustion process of quasi-steady diesel sprays is becoming clear. On the other hand, spray development in the actual engine very often occurs under non-quiescent conditions. A lot of investigations on these spray and combustion parameters mentioned above have been done in different optical engines [12, 13, 14, 15] with single-hole injectors. What's more, considering that multi-spray injectors are usually applied in real diesel engines, the influence of jet-to-jet interactions on combustion and soot formation have also been investigated by some researchers [16,17]. However, the information related to the influence of air flow brought about by piston movement on spray and combustion development is still limited. The characterization of swirl flow structure in a light-duty optical diesel engine was studied in [18, 19] by Particle Image Velocimetry (PIV) coupling CFD tools. Authors concluded that piston geometry effect on the flow asymmetry might be more responsible than the intake flow effect. In [20], a high fluctuation of lift-off length was found for measurements in the engine applied in the present paper. Cycle-to-cycle scattering of air flow may be one of the main reasons for this behaviour.

In the present work, experiments were performed in an adapted two-stroke optical diesel engine. High-speed Schlieren imaging was applied to detect the complete boundary of the non-reacting and reacting spray. However, a limit was found for this technique when measuring the non-reacting spray cases because of the strong air movement. As a consequence, a newly developed Ultraviolet Light Absorption (UV-LA) technique was also applied here for the vapor penetration measurement. Mie-scattering and OH* chemiluminescence were used to measure the liquid length and flame lift-off length (LOL) for non-reacting and reacting sprays separately. Additionally, PIV was used to characterize in-cylinder flow motion. Measurements were performed with single-hole nozzles, and the analysis will show that the interaction of the spray with a non-quiescent medium cannot be neglected.

Including the present introduction, this document is made up of four sections. The next section (Experimental Setup and Methodology) gives a detailed description about the experimental facility, different optical techniques, and the test plan which was investigated in this paper. In the third section (Results and Discussion), the characterization of in-cylinder airflow is presented. Next, the effects of airflow on both non-reacting and reacting spray are elaborated. Meanwhile, all these spray and combustion parameters are compared with experimental results from the Engine Combustion Network (ECN) [21] under quiescent conditions. The last section of the paper (Conclusions) summarizes some of the most important conclusions of this investigation.

EXPERIMENTAL SETUP AND METHODOLOGY

Test Rig

An optically accessible single cylinder two-stroke engine with three-liter displacement, 15.6:1 compression ratio and low rotational speed of 500 rpm has been used for these experiments, which is described in detail in [22]. A cylindrical combustion chamber is designed with a diameter of 45mm. This chamber has one upper access for the fuel injector, and four lateral orthogonal accesses. One of them is used for the pressure transducer whereas the other three are equipped with optical windows with geometrical dimensions of 88×37 mm and 28 mm thick. The Cross-sectional view of cylinder head is shown in [Figure 1](#). During engine operation, the block temperature is controlled by an external heating-cooling system. The intake air temperature and pressure are controlled by electrical resistors and an air compressor respectively. An injection takes place every 30 cycles, which guarantees that there is no remaining residual gas from previous combustion cycles and the ambient conditions in the chamber are kept constant between consecutive repetitions. A commercial common-rail piezoelectric injector equipped with a single-hole nozzle 0.082 mm in diameter was used in this study.

Thanks to the adequate cooling of the injector holder and the low injection frequency during operation, the nozzle tip temperature can be considered constant.

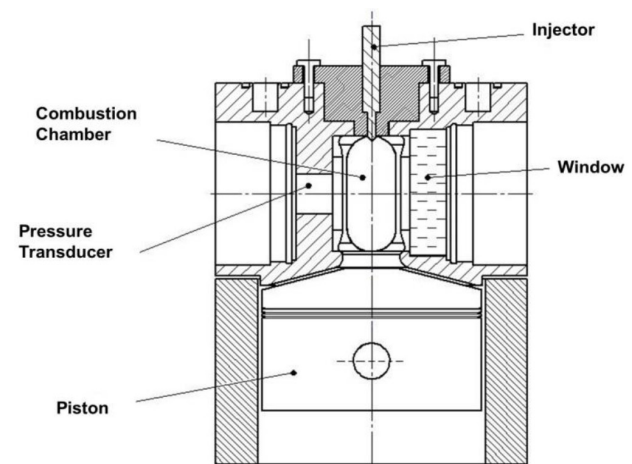


Figure 1. Cross-sectional view of cylinder head

Optical Techniques

As mentioned above, high-speed Schlieren and UV-LA imaging were applied here for measuring the vapor penetration under non-reacting conditions. The schematic of optical setup for non-reacting spray tests is shown in [Figure 2 \(a\)](#) and [Figure 2 \(b\)](#). As for the reacting spray tests, Schlieren and OH* chemiluminescence were applied simultaneously, as shown in [Figure 2 \(c\)](#).

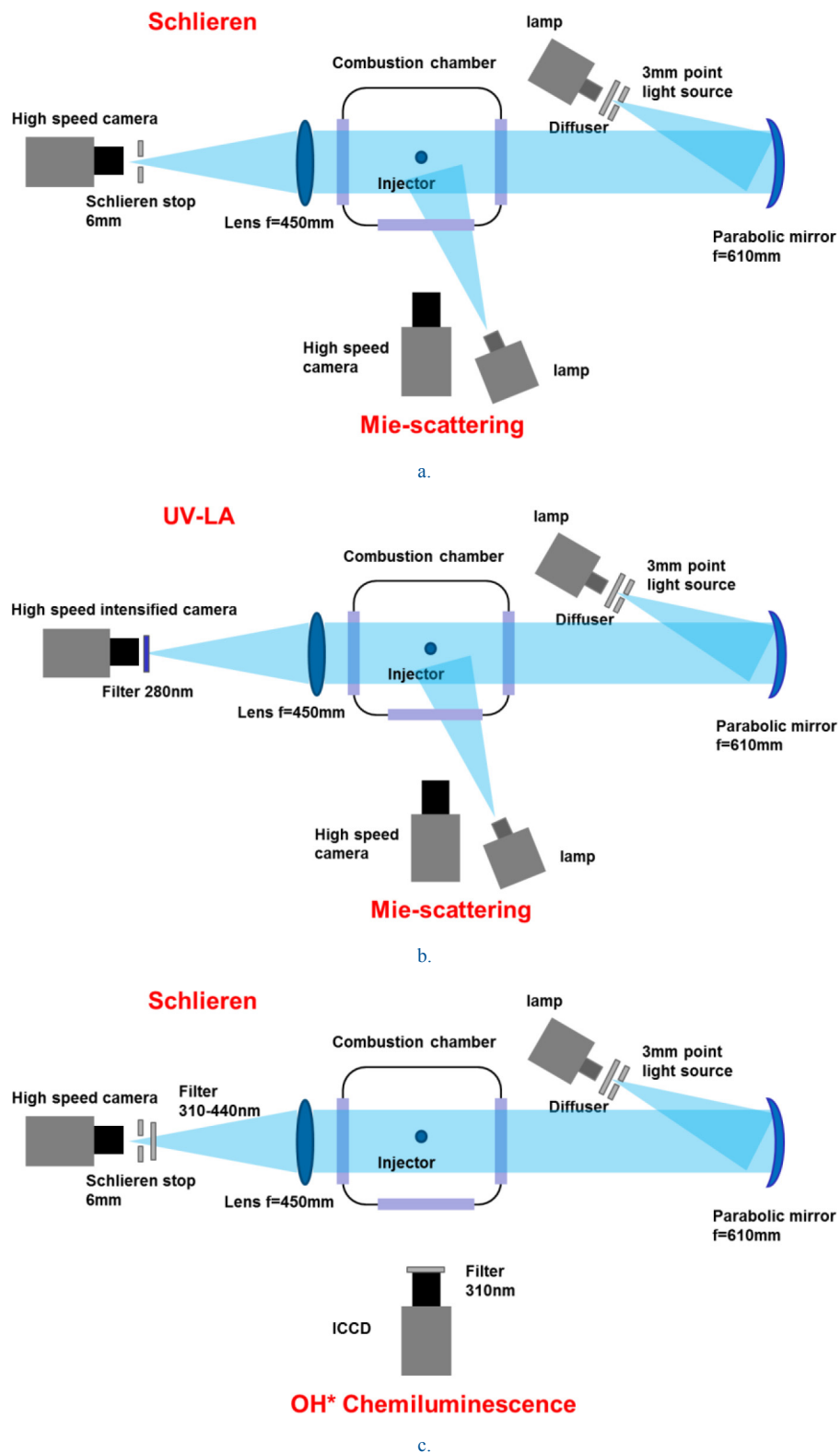


Figure 2. Optical setup (a) Schlieren and Mie-scattering (b) UV-LA and Mie-scattering (c) Reacting test

Schlieren Imaging

Schlieren imaging is a valuable technique for identifying density gradients, from which the spray area can be derived because of the density difference between vaporized fuel and ambient gases. The technique is based on the deviation suffered by a light beam, due to its refraction when crossing from one media to another, with different refractive index. This effect is known as beam steering. If a continuous non-homogeneous media is considered, the variation of the refractive index is represented by its gradient. Thus, it can be demonstrated that the deviation suffered by a light beam when traversing this media is proportional to the refractive index gradients within it [23]. Thanks to this phenomenon, the diesel spray has usually been able to be distinguished easily against the background light. In addition, besides spray tip penetration, ignition delay was also obtained from Schlieren images based on the analysis on the total intensity increment within the spray between each two following images. The detail of this processing methodology can be found in [24], where the corresponding time of the peak of the total intensity increment was defined as ignition delay and it was also validated by broadband chemiluminescence technique.

The actual Schlieren optical setup is shown in Figure 2 (a). A diffused point light obtained from a Xenon arc lamp was collimated by a parabolic mirror ($f=610\text{mm}$) which directs it through the combustion chamber. A spherical lens ($f=450\text{mm}$) was placed on the other side of the chamber to focus the light onto a so-called Fourier plane. A diaphragm (6mm) was used here as the Schlieren stop so that the light is later collected by the high speed-CMOS camera (Vision Research Phatron SA-5) running at 30,000 frames per second (fps) with a spatial resolution 6.8 pixel/mm. As for the reacting spray measurement, in order to eliminate soot radiation effect, a bandpass filter (310-440nm) was placed in front of the Schlieren stop (as shown in Figure 2 (b)) and the shutter time is reduced to $0.37\mu\text{s}$ compared with $9.85\mu\text{s}$ for non-reacting spray, while the other settings were kept the same with non-reacting one. In typical Schlieren setups, two parabolic mirrors are usually used off-axis at equal and opposite angles so that the off-axis aberrations eliminate each other. In this work, only one parabolic mirror was used, but the large focal length of the mirror has reduced the coma and astigmatism effects on the images.

UV-Light Absorption (UV-LA)

Besides Schlieren imaging, the vapor penetration of non-reacting spray was also measured by a developed UV-LA technique which is based on the ultraviolet (UV) light attenuation by the vapor phase [14, 25]. Because of this absorption for UV light, the intensity within the spray is much lower than that of the background gas area. As a consequence, the spray boundary was identified easily. The vapor optical thickness, KL, can be obtained according to the well-known Beer-Lambert law.

$$\log\left(\frac{I_0}{I_t}\right) = KL \quad (1)$$

where I_0 is the incident radiation, as obtained from images before start of injection, and I_t is the intensity of transmitted light. K is the dimensional extinction coefficient and L is the path length of the light

beam through the vapor phase. A fixed threshold of 20% the maximum KL value from KL images at each time position was applied here to distinguish the spray vapor phase and the background air.

The optical setup is quite similar with that of Schlieren imaging, as shown in Figure 2 (b). A continuous broadband 1000 W Xenon Arc lamp was used here as the light source to create the desired UV light. On the collection side, an intensified high speed camera Photron I2 coupled to an interference filter (centered at 280nm, with 10nm FWHM) was applied. Other settings were kept same as that of Schlieren. It must be noted that the UV light was also collimated by the parabolic mirror. The images were recorded at a speed of 8000 fps and a spatial resolution 8 pixel/mm.

OH* Chemiluminescence

Lift-off length was measured by recording the signal from OH* chemiluminescence, being a marker of the diffusion flame limits. A schematic of the actual optical setup is also shown in Figure 2(c). An Andor Solis iStar ICCD intensified camera equipped with a 100 mm focal length $f/2$ UV objective and a 310nm interference filter (FWHM = 10nm) was used. Only one image per injection event was recorded from 4ms to 5ms after start of energizing (ASOE) with a pixel/mm ratio of 10.9. One example of OH* radiation image is shown in Figure 3.

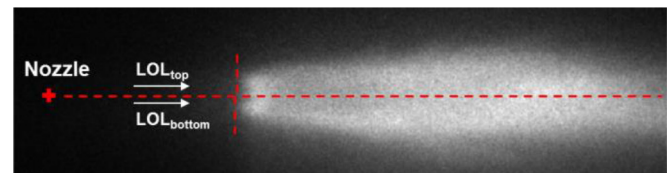


Figure 3. Schematic of LOL

Particle Image Velocimetry (PIV)

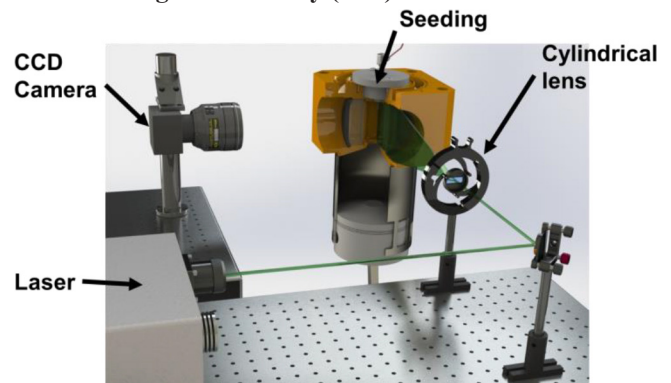


Figure 4. Schematic of PIV optical setup

To better understand the gas flow effects on spray behavior, it was decided to characterize the airflow movement within the combustion chamber under motored conditions by means of PIV. This technique is based on measuring the displacement of a cloud of particles between two consecutive images. For this purpose, a pulsed laser is usually employed to create an intense light sheet that illuminates the particles. The scattered light is registered by a CCD camera. A more detailed description of this technique can be found in [26] [27]. The optical set-up is depicted in Figure 4. A double-head pulsed Nd:YAG (2 lamps) laser was utilized to generate two pulses at 532 nm. The laser beam