An experimental study on Diesel spray injection into a non-quiescent chamber

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 quasi-stationary 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.

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, liquid length, flame lift-off length, ignition delay or even reacting spray dynamics have been investigated. 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 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. 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 x 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.

![Cross-sectional view of cylinder head](image)

**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).

(a)
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=610mm) which directs it through the combustion chamber. A spherical lens (f=450mm) 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 0.37µs compared with 9.85µs 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:

$$\log \left( \frac{I_0}{I} \right) = KL$$

where $I_0$ is the incident radiation, as obtained from images before start of injection, and $I$ 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% 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.

**Particle Image Velocimetry (PIV)**

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 was guided to the combustion chamber by means of a laser line mirror, while a cylindrical lens (-10 mm focal length) was used to transform the beam into a laser sheet with a frequency that can range from 0-15 Hz. A spherical lens (1000 mm focal length) was utilized to minimize the beam waist at the region of interest. The light scattered by particles was registered by a CCD camera, working under “frame-straddling” mode [28]. The straddle frequency is 7.5 pairs/s.

![Figure 4. Schematic of PIV optical setup](image)

Measurements were performed, under motored engine conditions, i.e. only the piston-induced flow was measured. Thermodynamic conditions at TDC correspond to $p_0 = 19.27$ bar and $T_0 = 760$ K. In-cylinder air was seeded with injection rate test fluid injected directly into the combustion chamber through the same injector as in spray investigations. In this case, a long injection is performed just after the Exhaust Vent Closure (EVC), which occurs at -90º ATDC. Because of the low volatility of the test fluid, as well as the reduced TDC temperature compared to the later spray injection studies (check Table 1), the oil droplets did not vaporize. Injection pressure was set to 1000 bar, so a good agreement between uniformity and quality of the images was obtained. Taking into account the range of velocities existing in the combustion chamber for the conditions chosen, the two laser pulses were separated 10 ms. Six different planes within the combustion chamber were measured. In Figure 5, a scheme of the distribution of the region of interest is shown. Two perpendicular planes intersecting on the spray axis (labelled as C and CC respectively), were chosen together with the corresponding parallel planes separated 10 mm on both sides of the combustion chamber, which are labelled as L (left), R (right), F (front) and B (back), respectively. Therefore, it was possible to determine not only the flow pattern, but also any possible asymmetry. Planes F-CC-B are within the line of sight of the later arrangement for Schlieren and UV-LAS visualization, and will be used for subsequent analysis. Measurements were performed from -10 to 15º, with 1º increments. For each plane and instant, 75 cycles were recorded. It has to be
noted that only one velocity map was recorded per engine cycle. To get an estimation of a theoretical limit to velocity, the maximum piston speed has been compared to the measured PIV field. If an incompressible steady flow is assumed, the following equation would give an estimation of the maximum chamber velocity:

\[ V_{\text{chamber}} = V_{\text{piston}} \cdot \left( \frac{A_{\text{piston}}}{A_{\text{chamber}}} \right) \]  

(2)

Giving values to the maximum piston speed (~4.6m/s) and areas, the maximum chamber velocity is 51 m/s, which is far above the maximum PIV measured value (20 m/s), as will be shown in later section.

Test Matrix

The operating conditions forming the test matrix are summarized in Table 1, where in-cylinder conditions are parametrized in terms of TDC temperature \( T_a \) and density \( \rho_a \). The operating point NO (nominal condition, \( T_a=870K, \rho_a=22.8kg/m^3 \)) was chosen as the baseline condition. Parametric variations in injection parameters (injection pressure) and thermodynamic conditions within the chamber at TDC (ambient temperature and ambient density) were performed both under non-reacting (in-cylinder mixture contained pure nitrogen) and reacting conditions (injection into ambient air, with 21% oxygen (vol.)). The test matrix also includes a condition denoted as SA that reproduces TDC conditions similar to the so-called Spray-A condition from ECN, but at 21% oxygen volume fraction. This makes it possible to compare the evolution of sprays in the present combustion chamber with ECN data measured in a constant pressure chamber, where thermodynamic and flow conditions are nearly quiescent and steady. The PIV operating condition was presented in the last row of Table 1.

A common rail single-hole injector fitted with a 82µm nozzle has been used in the experiments. The fuel used throughout these tests was n-Dodecane for all techniques except for the UV-LA imaging technique, where 80% of dodecane (in mass) was blended with a blend of additional components with high absorptivity for UV light. More information about this blend can be found in reference [27]. For all experiments performed within the present study, 30 injections have been recorded at each operating condition to reduce measurement uncertainties due to engine operating variability.

![Figure 5. Scheme of the distribution of the PIV measuring planes.](image)

### Table 1 Experimental conditions

<table>
<thead>
<tr>
<th>Operating point</th>
<th>( P_{\text{inj}} ) [bar]</th>
<th>Air T ((T_a)[K])</th>
<th>Air Density ((\rho_a)[kg/m^3])</th>
<th>Oxygen [%]</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO</td>
<td>1500</td>
<td>870</td>
<td>22.8</td>
<td>0/21</td>
<td>Baseline</td>
</tr>
<tr>
<td>SA</td>
<td>500/1000/1500</td>
<td>900</td>
<td>22.8</td>
<td>0/21</td>
<td>ECN-Spray A</td>
</tr>
<tr>
<td>MT</td>
<td>1500</td>
<td>830</td>
<td>22.8</td>
<td>21</td>
<td>Medium T</td>
</tr>
<tr>
<td>LT</td>
<td>1500</td>
<td>780</td>
<td>22.8</td>
<td>21</td>
<td>Low T</td>
</tr>
<tr>
<td>LD</td>
<td>1500</td>
<td>870</td>
<td>15.2</td>
<td>0</td>
<td>Low density</td>
</tr>
<tr>
<td>PIV operating condition</td>
<td>-</td>
<td>760</td>
<td>19.27</td>
<td>0</td>
<td>Motored condition</td>
</tr>
</tbody>
</table>
To determine the intake pressure and temperature values required to achieve the target TDC conditions, an accurate characterization of the engine has been performed. Thermodynamic conditions inside the cylinder have been calculated from measured pressure, using a first-law thermodynamic analysis. An example of the in-cylinder pressure and density temporal evolution during the injection event at NO condition is plotted in Figure 6. The injector was energized starting at -6.35° ATDC, while the actual injection starts at around -5.35° ATDC, to minimize piston-induced volume variations conditions during the injection event. The energizing time was set as 4ms, which results in an injection duration of 5ms (15º), approximately.

As piston approaches TDC position, velocity values decrease, but the high velocity region is observed to move closer to the nozzle and towards the left part of the combustion chamber. Near TDC this high velocity region vanishes drastically, as expected. However, a clockwise vortex appears on the right part of the combustion chamber. This flow structure seems to move towards the left of the combustion chamber and disappears as the piston moves down and the outlet flow speed increases.

Results and Discussion

In-cylinder airflow under motored conditions

Velocity fields of the airflow corresponding to the plane CC are shown in Figure 7. They have been obtained by averaging the velocity magnitude from 75 repetitions. One velocity map is shown every 2° during the injection event (from -5° to 9°), as representative of the global behavior. The color map corresponds to the velocity magnitude (i.e. the modulus of the 2D projection of the velocity vector on the measurement plane), while the black lines represent the flow stream lines. At -5° ATDC the airflow is entering into the combustion chamber at more than 20 m/s, while at the upper part of the combustion chamber the speed is reduced to 5 m/s approximately.

A comparison of the averaged velocity fields among different planes at -5° ATDC is shown in Figure 8. Differences in magnitude and distributions can be observed among the different measuring planes which indicate the flow field is not symmetric within the combustion chamber. Velocities on L and B planes are usually higher than that on R and F respectively. The main consequence of these observations is that, the spray tip can be slowed down by the airflow and even displaced towards one side of the combustion chamber, as will be shown in later sections.
Non-reacting spray analysis

After the analysis of in-cylinder flow, Schlieren and Mie-scattering results are analyzed to describe non-reacting spray behaviour. The tip penetration of n-Dodecane at NO1500 and LD1500 are shown in Figure 9. In this figure as well as in the subsequent ones presented in this paper, the time is referred to the start of injection with the acronym ASOI (After Start of Injection) and all the plots represent the average value from 30 repetitions. The corresponding standard error (SE) with 95% confidence level is also included. From Figure 9, the spray vapor of LD1500 is seen penetrating faster than that of NO1500 due to lower air entrainment because of the lower density, which is consistent with previous research [1]. However, these penetration curves tend to level-off after around 50mm, while the optical limitation is around 80mm. It looks as if these sprays ‘stop’ in the middle of combustion chamber. This phenomenon is considered as Schlieren limitation which is marked with the gray region.

Two examples of processed Schlieren images at two different time position are shown at the top of Figure 10. At start of injection (1200µs), fuel mass fraction within vapor phase is high, and accordingly density gradients are also important, which makes it possible for the processing routine to capture the spray boundary precisely, which is done based on a fixed threshold. However, with the increase of air entrainment further away from the nozzle, fuel mass fraction at spray tip decreases, and so do spray-induced density gradients. On the other hand, the velocity of the air at the other end of the chamber is much higher than that of upstream spray, as shown in previous PIV maps, which can also increase the air entrainment and make spray become thinner. In addition, the high flow velocity on that end of the chamber also creates a deflection of light rays, which produces a non-uniform time-variable background. As a result, the detection of the spray is not accurate enough, as it gets diluted into the noisy background. This can be seen in the Schlieren image at 3200µs in Figure 10, for which a spray almost as long as the previous image at 1200 µs is detected. This explains the levelling-off effect shown on Schlieren penetration plots (Figure 9).

To avoid the previous shortcomings from the Schlieren technique, UV-LA visualization was carried out, where the only absorbing media should be the fuel. As mentioned above, in order to get high absorptivity for UV light when doing UV-LA tests, 80% (in mass) n-Dodecane was blended with a highly-absorbing surrogate, detailed in [27]. The resulting fuel was investigated with Schlieren, Mie scattering and UV-LA techniques and compared against pure n-Dodecane in the first two techniques. Figure 9 and Figure 11 present a comparison of Schlieren-derived vapor penetration and Mie-derived liquid length of both fuels at NO1500 and LD1500 points. Apparently, as shown in Figure 9, fuel effects on vapor penetration are negligible, because momentum flux, which is the main driver for penetration, does not depend on fuel properties when operating at constant injection pressure, which is coherent with previous research [29]. As a consequence, it can be concluded that vapor penetration of this mixture fuel can be applied to represent that of n-Dodecane. On the other hand, fuel composition is seen to have an influence on the liquid length, as shown in Figure 11. The liquid length of the mixture penetrates further because of the lower volatility, but maximum differences are less than 2 mm, note that the absorbing fuel has still a large proportion of n-dodecane. Liquid length is also shown to slightly increase during the ending period of injection because of the ambient density decrease caused by the piston moving down from around 3º ATDC. Summing up, the chosen fuel mixture will behave very similarly to n-Dodecane as for vapor spray evolution.

Finally, Figure 12 shows tip penetration temporal evolution of mixture obtained both from Schlieren and UV-LA techniques at NO1500 and LD1500 points. It can be seen that the results from both techniques are consistent when the penetration is shorter than 50mm. After that, UV-LA is still able to capture the spray tip very well until
the optical limit, which is also confirmed by the UV-LA image at 3500µs in Figure 10. That is because ambient gas shows a quite low absorptivity for UV light compared with that of the vapor phase of the mixture spray and it is easy for the processing routine to identify the dark spray against the bright background. As a conclusion of this section, UV-LA performs better than Schlieren on capturing tip penetration for the non-reacting spray under non-quiescent conditions and the penetration value of n-Dodecane will be replaced with that of this mixture fuel for further analysis because of the negligible fuel effects.

\[ S_{\text{scale}} = S \cdot \sqrt{\frac{d_{\text{ENG}}}{d_{\text{ECN}}}} \]  

(4)

where \( S_{\text{scale}} \) is the scaled penetration which will be used in the following comparison, \( d_{\text{ENG}} \) and \( d_{\text{ECN}} \) are the nozzle orifice diameter used in the optical engine and ECN tests, respectively.

Figure 13 shows the temporal evolution of tip penetration under SA non-reacting conditions for three injection pressures from both facilities. It has to be reminded that ECN vapor penetration was processed from Schlieren images, while engine data was obtained from UV-LA tests. It can be seen that, at start of injection, the vapor penetration from the engine is consistent with that from ECN. However, after around 40mm, divergence between both sets of data appears, and becomes larger with time. Although, the density drop due to piston motion might contribute to an increase on penetration velocity, the density difference from TDC to the end of injection is just around 2.5kg/m3, thus, its influence would be considered negligible. On the contrary, the gas flow was considered to play the main role.

One example of the temporal evolution of spray shape obtained from UV-LA at SA1500 condition is shown in Figure 14. The injection time and corresponding crank angle are marked on the top left and top right of this figure respectively. It can be seen, at early stage of injection (-3.25° ATDC), the spray shape is cone-like, which is same as that under quiescent condition. This is because the spray is still far away from the window bottom and the velocity of ambient gas in that zone is quite low compared with the spray velocity, as shown in PIV images. However, from 2° ATDC to 5° ATDC, the spray geometry is much more complicated than a cone shape. First, the spray tip part becomes flat and then, some part at spray side is moving back. The PIV-derived flow streamlines are overlaid onto the UV-LAS images. It must be noted that PIV results were obtained under different in-cylinder conditions, to avoid evaporation of seeding test fluid. However, in a first approximation, the flow can be assumed to be the same due to the operation of the engine at the same rotational speed. A strong airflow was found at the bottom side moving in opposite direction towards the spray, with a clockwise vortex. The spray can be seen to follow such a flow pattern, which results in a much wider non-symmetrical spray tip.

In addition, standard error of penetration is also detecting this airflow effect, as shown in Figure 13. SE of engine measurements shows a small value at start of injection, very similar to the ECN ones for a quiescent ambient. By 1.5 ms SE in the engine rises clearly above ECN results, which approximately coincides in time with the departure of the average penetration plots. Note that engine measurements are carried out with a much larger sample size (30 injections) than ECN ones. Therefore, air flow effects are observed in terms of both a slow-down of the average spray penetration, and also of an increase of shot-to-shot scattering. On the other hand, the lower injection pressure case also included in the plot shows a higher SE during the later phase of injection, which may be caused by the lower momentum within the spray at this lower injection pressure, which makes it more prone to disturbances from the air flow.

**Comparison with quiescent chamber results**

As a reference experiment under quiescent chamber conditions, the Spray A condition defined by ECN [20] has been chose, because it has the same density and temperature as defined at TDC for the SA operating point in the test matrix. The ECN database used here was obtained under quiescent conditions with n-Dodecane in a constant pressure vessel. A complete description of the facility is given in [30]. In addition, the standard Spray A injector was equipped with a single-hole nozzle with a diameter 90µm.

On the other hand, for a mixing-controlled spray injected into a quiescent ambient, vapor tip penetration under constant injection and ambient boundary conditions can be described by the following equation:

\[ S = k \cdot u_0 \cdot d_0 \cdot \frac{\rho_g}{\rho_f} \cdot t \]  

(3)

where \( d_0 \) is the orifice diameter, \( u_0 \) is injection velocity, \( \rho_g \) is ambient gas density, \( \rho_f \) is fuel density, \( t \) is time after start of injection and \( k \) is a proportionality constant that can be related to the air entrainment rate[31]. Compared to ECN data, the same fuel and injection pressure are used, and hence a similar injection velocity can be expected. Average chamber density in the engine for SA condition should also be similar to the nominal ECN one. Therefore, to enable a comparison between both sets of data, ECN results were scaled by orifice diameter as shown in the following equation:

![Figure 12. Schlieren and UV-LA comparison at NO1500 and LD1500 conditions](image-url)
Reactive spray analysis

Spray tip penetration was measured with high-speed Schlieren under reacting conditions, where the high refractive density gradient created by combustion gives a very intense Schlieren signal, without the shortcomings of the non-reacting cases. A sequence of images of reacting spray temporal evolution at SA1500 were shown on the right of Figure 15, meanwhile, the non-reacting ones from UV-LA at corresponding time were shown on the left as reference. At start of injection (200µs), there is still no combustion happening, thus, the spray behaves as under non-reacting conditions, and there is no expansion neither in axial nor in radial direction. At that time, airflow influence is still non-significant as spray is far away from the high velocity zone. Around the ignition timing (700µs), combustion leads to a fast radial expansion on the spray, which produces such a slowdown of the spray tip penetration that it is even shorter than the non-reacting one. From 1200µs to 2200µs (around -2 to 1° ATDC), spray tip is entering into the high velocity field zone. It can be seen that the tip penetration of reacting spray is being kept shorter than the non-reacting one. One speculation is that the airflow influence on reacting tip penetration might be stronger than the non-reacting one owning to the lower density caused by combustion within spray.
The effects of TDC temperature on ignition delay and lift-off length were presented in Figure 17 and Figure 18 respectively. Note that the temperature sweep was carried out at constant TDC density, oxygen content and injection pressure. ECN data under the same ambient density, oxygen concentration and injection pressure was also shown here as a reference. There may be a nozzle diameter effect on ID, but there is no simple re-scaling as in the case of penetration, so no correction has been performed. As for LOL, ECN data have been scaled according to the empirical result from Siebers [5] [6]

\[ \text{LOL}_{\text{scale}} = \text{LOL} \cdot \left( \frac{d_{\text{ENG}}}{d_{\text{ECN}}} \right)^{0.34} \]  

Both ID and LOL exhibit a much lower sensitivity to in-cylinder temperature compared to results under quiescent conditions. It is remarkable that above 850K of both parameters are almost constant. These results are difficult to explain with the present data. CFD analysis is underway to clarify if flow interaction could also have an influence on this result. On the other hand, while standard deviation of ID is pretty similar in both facilities, for LOL the standard deviation of the engine is much larger than that of quiescent data, which is consistent with previous work [20] and could stem from flow interaction.

Finally, the effects of TDC ambient temperature on spray tip penetration and corresponding SE were shown in Figure 19. It seems the temperature does not have significant influence on penetration (except SA1500) which is different from the observed trend under quiescent conditions [10][11] where the spray shows a faster penetration with higher temperature. In addition, SE shows a fast increase after ignition (ignition delay is shown in Figure 17) and it increases with higher temperature. This trend might be explained with similar ID and LOL (as shown in Figure 17 and Figure 18), which may contribute to a similar radial and axial expansion on spray under the same ambient density.

Conclusions

In this paper, the characteristics of diesel spray injected into a non-quiescent chamber under both non-reacting and reacting conditions with a single-hole injector were investigated. The liquid length, spray tip penetration, ignition delay and flame lift-off length under different thermodynamic conditions and injection pressure values were measured with different kinds of optical techniques. Some parameters were also compared with ECN data from a constant-pressure vessel.
where the ambient condition was considered as quiescent. In addition, in order to have a better understanding about the gas flow effects on spray behavior, the in-cylinder airflow velocity field was also measured with PIV technique. Some important conclusions of this study are summarized as follows:

- Before TDC, the airflow velocity at the lower part of the chamber was very high compared to the nozzle area. Some vortexes due to the reversing motion of the piston at the end of compression and start of expansion were found, which interacted with the injection event. Thanks to the measurement at different planes, it was found the velocity field in the combustion chamber was not symmetric.

- Under non-reacting conditions, Schlieren technique was not able to identify spray tip very well when it penetrated more than 50mm because of the interference from airflow. A UV-LA technique was developed and it works better on capturing spray penetration under such non-quiescent condition when the spray becomes diluted and the Schlieren effect from the spray is not strong enough compared to the background.

- As for the non-reacting spray, the tip penetration from the engine was kept almost consistent with ECN data at the start of injection. When it came to the high velocity region of airflow (around 40mm), the spray was slowed down owing to the aerodynamic force and vortexes from airflow.

- As for the reacting spray, the divergence of tip penetration with the ECN data appears earlier than that of non-reacting spray. Both ignition delay and flame lift-off length from the engine show much less sensitivity with ambient temperature sweep. Ambient temperature did not have significant effect on spray tip penetration.

References


23. Settles G. S., Schlieren and sadowgraph techniques: visualizing phenomena in transparent media (Experimental Fluid Mechanic), Springer Verlag, Heidelberg, Germany, 2001

DEFINITIONS/ABBREVIATIONS

TDC 
ECN 
LOL 
UV-LA 
CMOS 
PIV 
ATDC 
FWHM 
ASOI 
ASOE 
T_a 
ρ_a 
EVC 
ID 
SE

top dead center 
engine combustion network 
lift-off length 
ultraviolet light absorption 
Complementary Metal Oxide Silicon 
particle image velocimetry 
after top dead center 
full width at half maximum 
after start of injection 
after start of energizing 
Ambient temperature 
Ambient density 
exhaust vent closure 
ignition delay 
Standard error

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