

Schlieren Methodology for the Analysis of Transient Diesel Flame Evolution

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ABSTRACT

Schlieren/shadowgraphy has been adopted in the combustion research as a standard technique for tip penetration analysis of sprays under diesel-like engine conditions. When dealing with schlieren images of reacting sprays, the combustion process and the subsequent light emission from the soot within the flame have revealed both limitations as well as considerations that deserve further investigation. Seeking for answers to such concerns, the current work reports an experimental study with this imaging technique where, besides spatial filtering at the Fourier plane, both short exposure time and chromatic filtering were performed to improve the resulting schlieren image, as well as the reliability of the subsequent tip penetration measurement. The proposed methodology has reduced uncertainties caused by artificial pixel saturation (blooming). Additionally, an algorithm to calculate Lift-off length from schlieren images has been developed and compared to the more conventional OH* imaging technique.

By means of the improved setup, the analysis of transient diesel flame has been performed throughout the ignition and early combustion phases. When compared to a non-reacting vaporizing spray, the temporal evolution of the reacting case departs from the inert one at the start of combustion, when expansion in both axial (i.e. spray tip increase) and radial direction are observed. After that, the tip penetration progressively decreases on a clear transient period where the flow tries to re-organize itself in response to the induced reaction zone. Eventually, the spray undergoes an acceleration period where the reacting spray tip progresses above the non-reacting one. A parametric study has been conducted for three injection pressure levels to investigate the influence of this parameter upon transient flame evolution.

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INTRODUCTION

The progressively more restrictive regulation on exhaust emissions is the main motivation that drives researchers when characterizing the pollutant formation mechanisms within Diesel flames. In this sense, fuel-air mixing process within Diesel spray plays a fundamental role and therefore, the investigation on such mixing mechanisms and their impact on engine performance have been pivotal in recent years [1, 2, 3, 4].

In that sense, the use of optical techniques provided both qualitative and also quantitative data about mixing processes in terms of the fuel-air composition within the spray. Regarding local quantification under non-reacting conditions, techniques like Laser Induced Fluorescence [5, 6, 7] or Light Absorption Scattering [8,9] can provide reliable fuel-air equivalence ratios. However, the main drawback of such techniques is the difficulty in obtaining a time-resolved

description of a single injection process because of the weak signals and the need of intensified cameras (commonly with low recording frequency); not to mention inherent difficulties such as signal quenching [7] and also the calibration needed to convert pixels counts into final fuel-air equivalence ratio.

On the other hand, schlieren/shadowgraphy technique can provide a single-injection time-resolved description of spray tip penetration and cone angle [10, 11, 12], which are indirect parameters of how the fuel-air mixing process develops. Based upon the same measurement principle, namely the steering of light rays when going through a medium where density gradients exist, the only difference between both techniques is the use of a cut-off at the Fourier plane for schlieren, which enhances contrast but may also induce some loss of information, whereas no cut-off is used for shadowgraphy. Such measurements have helped validate penetration scaling law models [13] as well as mixing-controlled 1D spray models derived from gas-jet theory

[14,15] and even CFD models [16]. The widespread use of such measurements for validation purposes underlines the potential of schlieren when investigating Diesel sprays [17].

Schlieren/shadowgraphy visualization can also be applied to the study of the reacting phases of diesel spray evolution. The measurement principle indicates that combustion-induced drop in density should be captured by the technique, and this should enable macroscopic characterization of the diesel flame.

Compared to direct flame visualization, which is mainly focused on the chemically active parts of the Diesel flame, schlieren should also be sensitive to the presence of hot combustion products, even if they are outside of the reaction front. Few studies can be found in the literature [17,18] that make use of schlieren/shadowgraphy visualization for the analysis of reacting spray. Furthermore, when looking into the described trends of reacting tip penetration compared to the inert one, results are somewhat non-consistent. By means of shadowgraphy, Picket et al. in [19] have reported reacting spray results that penetrated slightly faster than the inert one. Moreover, the same author in [20] using the same optical setup but adding a schlieren cut-off (which are not used in shadowgraphy imaging) reported that the reacting spray progressed slightly more slowly than the inert case. Additionally, they showed that the spray seems to disappear during the cool-flame period. In more recent studies reported at Engine Combustion Network (ECN) workshops, schlieren was performed at different facilities with identical test conditions and very similar optical setups [12]. Results have shown that the measured reacting penetration tendencies varied among different laboratories. Authors argued that differences in penetrations were associated to background (hot/cold ambient gases) schlieren sensitivity as well as to the soot luminosity that interfered on the processing steps.

Besides ambient conditions, the optical set-up and the schlieren/shadowgraphy sensitivity seem to affect the vapor fuel-related information that is eventually displayed in a schlieren image. Furthermore, there are cumbersome issues when digital analysis is applied to the resulting images that include: artificial pixel saturation, i.e. blooming phenomenon [21] or unusual histogram distributions [22], which limit or at least introduce uncertainty when systematic measurements are performed. Therefore, when considering the discrepancies among configurations from different authors (schlieren sensitivity, interfering soot luminosity and processing tools), it might seem reasonable that the corresponding reacting tip penetration trends may not fully agree [17, 18, 19, 20].

After the previous state-of-art description, the present work tries to contribute to the description of the reacting Diesel spray by making use of schlieren visualization. The main goal is to make a comparison of spray tip penetration evolution when shifting from inert to reacting conditions. According to the last two paragraphs, one of the main guidelines of this investigation is to try to develop a schlieren optical set-up that minimizes uncertainties associated to the application of the technique to Diesel sprays by removing

soot luminosity, which in turn improves digital analysis of the images and the quantitative evaluation of the penetration behavior.

In addition to these issues there are indications, yet not exploited, about the potential of schlieren images to provide measurements of lift-off length when a schlieren contour is overlaid on a simultaneous OH* chemiluminescence image [20]. Therefore, a purpose-developed routine for schlieren lift-off measurements was implemented based on high-speed recording, which also adds the possibility of measuring a time resolved lift-off length, together with other common spray parameter extracted from schlieren images (penetration, spray angle, SOC, etc.). The methodology was tested and compared to simultaneous OH chemiluminescence measurements performed in a Constant-Pressure Flow (CPF) vessel.

In this paper, the above introduced topics are discussed as follows: First the experimental apparatus used on this investigation is presented. In the subsequent diagnostics and measurements section, the optical set-up and the implication of removing soot luminosity are addressed, together with the final results obtained from digital analysis. Furthermore, the definitions and steps followed on the schlieren lift-off routine are discussed, as well as the OH image analysis procedures. The results section summarizes the main outputs of the proposed methodology. First, the significance of schlieren-derived Lift-off Length measurements is discussed compared to OH*-derived one. Reacting spray penetration is compared to the inert one, and the effect of increasing the injection pressure is addressed. Lastly, the summary/conclusions section contains the most important findings of the present work.

EXPERIMENTAL APPARATUS

TDC engine-like thermodynamic conditions were simulated on the High-pressure&High-Temperature test rig shown in [Figure 1](#). This constant-pressure flow (CPF) vessel is filled with gases that can be pressurized and heated up to 15 MPa and 1000 K, respectively. Electrical resistances provide the energy to heat up the gas to a target temperature selected by the user on a PID control, which also controls the pressure level inside the vessel. The double layer wall configuration of the vessel enables improvement on homogeneity of the temperature distribution inside the chamber. Heat transfer losses to the room ambient have been limited by (i) an isolating material that fills the space between the surfaces in contact with the gas and the ambient, and (ii) a secondary electrical resistance that heats up the outer layer of the combustion vessel.



Figure 1. High Pressure-High Temperature test rig

The facility can be operated in either open or closed loop. In the former case, dry air is supplied by a volumetric compressor. In closed loop configuration, a N_2/O_2 mixture at controlled concentration is continuously re-circulated. Downstream the combustion vessel, a cyclonic filter removes non-vaporized fuel from the gas flow, avoiding ambient saturation with fuel. The gas velocity across the chamber has been estimated to be minor compared to the spray velocities even at far distances from the spray tip, with approximate values of 0.2 m/s and 0.4 m/s. As a consequence, the shot-to-shot spray dispersion is reduced when compared to optical engines and rapid compression machines because of the steady flow configuration. Since high temperatures are continuously flowing around the injector tip, a water coolant circuit has been drilled in the injector port to maintain the user selected constant and safe temperature on the injector body (363 K on spray-A studies). An independent electronic system controls injection frequency during the experiments, being 0.5 Hz for this investigation.

Four orthogonally drilled ports provide access to the combustion chamber. The first one is occupied by the injector port and the cooling system for the injector body. The other three accesses are equipped with round quartz windows (128mm) in a T-shaped path providing both perpendicular access and frontal view for spray analysis of single-hole nozzles and multiple-hole nozzles, respectively.

OPTICAL DIAGNOSTICS AND MEASUREMENTS

Schlieren Visualization and Optical Set-up

The shadowgraph effect is a common phenomenon found in some everyday life situations. Based upon the variation of the refractive index (n) of a target gas/liquid, the shadowgraph effect produces a deviation of light beams from the original path creating a shadow when they travel through a nonuniform medium towards an observer. The relationship between refractive index and density, which is a more useful variable in terms of spray studies, has been mathematically

described in [23] through Equation 1, where the refractive index is expressed in terms of the Gladstone-Dale number (k) and the density of the gas/liquid (ρ).

$$n = k \cdot \rho + 1$$

(1)

The application of a shadowgraph to measure vapor phase penetration requires a detailed control and knowledge about the propagation of light through the medium (e.g. engine combustion chambers [24] or vessels [13]). The simplest scenario for the shadowgraph visualization is that of creating a parallel orientated light array from a point light source using a lens as observed on the Figure 2a. On the A-A plane, one can observe different levels of light intensity due to the deviation with respect to the original propagation direction for each of the effects considered in the plot.

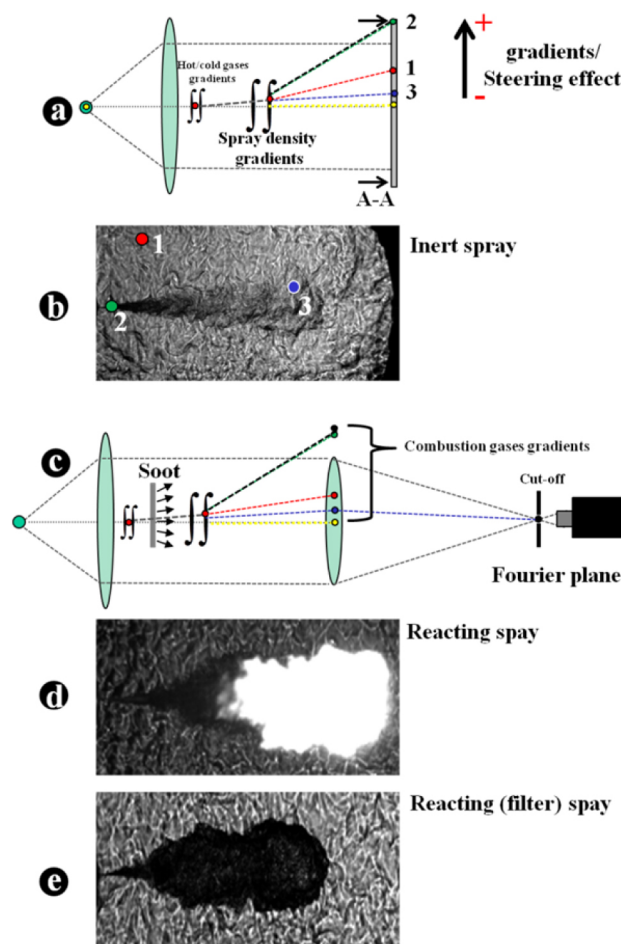


Figure 2. Sketch of the schlieren phenomenology for Diesel spray studies

Starting with at a theoretically unperturbed ray that does not interact with the spray (label “1” in Figure 2b), once it transits through a non-uniform medium, it suffers a deviation or steering process as a consequence of local non-uniformities that results in a shift (red spot upon the A-A plane) compared to the original path (yellow spot) in Figure

2a. When considering light beams that interact with the fuel spray, variable fuel-air composition (and hence refractive index) can be expected. The deviation magnitude depends on the local fuel-air mixture density gradients. Steepest gradients can be found inside the liquid core and close to the nozzle (label “2” in [Figure 2b](#)), whereas lowest gradients occur far away from the nozzle (label “3” in [Figure 2b](#)). Accordingly, a deviation range can be expected according to the location within the spray. Notice that spray mixture gradients could match the steering effect induced by hot and cold gases (label “1” in [Figure 2b](#)). On the other hand, lean mixtures (equivalence ratio near zero) could mimic the path of unperturbed rays (zero deviation) as long as the ray is re-oriented. Such rays would avoid the schlieren cut-off on the Fourier plane, and would go back to the original unperturbed path (yellow spot) as depicted in [Figure 2c](#).

As a consequence of heat release, the increased temperature inside the flame core creates a density gradient which is directly related to a steering originated by combustion gases in [Figure 2e](#) (filtering will be discussed on latter sections). It is difficult to predict how strong steering by hot combustion gases is. However, it can be hypothesized that such combustion-induced steering can be similar to liquid deviation, since the dark levels in [Figure 2e](#) are quite similar to the ones in label “2” in [Figure 2b](#).

The presence of soot within the flame results in the emission of light that does not perturb the induced schlieren effect as seen in [Figure 2d](#) along the spray. However, soot radiation can be problematic when inducing pixel contamination (blooming phenomenon [20]) in high intensity zones. As a pixel reaches the maximum dynamic range of the camera, it may excite surrounding pixels. Therefore, the background could be part of the resulting spray zone detected by the processing routine. As a consequence, over-predicted penetration results could be expected.

The needs of confining all of this information into a small camera sensor by means of a lens result in additional issues. As shown in [Figure 2e](#), the finite size of collecting lenses as well as the distance between the lens and the schlieren location could limit the capability to have a controlled schlieren system. In this sense, Pastor et al. used systematic analysis in [25] to provide better understanding of how different optical systems resulted into different images appearance and consequently a scattering in the final spray penetration measurements. They concluded on the needs of having a controlled schlieren system by: (i) adding a cut-off on the Fourier plane where all collected light (ii) minimizing the distance between the spray and the collecting lens and (iii) maximizing the camera lens size. All three issues are intended to avoid non-intended light clipping, i.e. uncontrolled schlieren effect.

The “focused single pass” schlieren setup [23] in [Figure 3](#) helped overcome the blooming problematic as it will be discussed latter on this paper. This optical arrangement can be divided in two different sections, which are referred to as the illumination and collection sections. Upstream the spray

on the illumination section, a coherent and parallel light ray array was created by placing a diffused point light source at the focal length of a parabolic mirror ($f=610$ mm). This diffused pointed source (iris clear aperture of 2mm) has been obtained by integration of the light coming out of a Xenon arc lamp through a liquid light guide and orienting the light orthogonally to the vessel. The visualization area was maximized because of the mirror diameter (150 mm) being larger than the optical windows (128 mm).

Downstream the spray on the collection section, a spherical lens is placed after the combustion vessel that concentrates the light onto the so-called Fourier plane, where a round cut-off (iris clear aperture of 4 mm) was placed. The camera (Vision Research Phantom V710) is placed right after this plane together with a commercial lens that finally drives all the light beams onto the camera chip.

Settles has reported [23] some issues to be considered when using the optical configuration depicted in [Figure 3](#). On the one hand, the theoretical point light source is far from the real 2-mm extended light source used in this investigation. Light ray parallelism on the illumination section could be uncertain because a right focusing of the parabolic mirror cannot be guaranteed all over the light source width. However, in previous work [25], Pastor et al. demonstrated that varying the width of the light source (comparison between 1mm and 6 mm) only affects the measuring range of the schlieren system, but neither the sensitivity, nor background illumination, nor the most important parameter, i.e. the tip penetration value. As the optical set-up in [Figure 3](#) is similar to that found in [25], measurements in the current configuration should be accurate regardless the extended light width.

On the other hand, matching a parabolic mirror with a spherical collection lens usually causes optical aberrations. Astigmatism is the more-likely aberration in configurations such as [Figure 3](#), due to differences on the path length along the optical centerline and the parabolic mirror periphery due to the off-axis tilt. Here, the off-axis angle of the extended light source with respect to the parabolic mirror was reduced to avoid or minimize the aberrations. In this sense, Settles indicates that Z-type arrangement is the most extended solution to overcome astigmatism, since off-axis angles are reduced to their minimum. The drawback when using such optical array in CPF vessels is the imperative far location of the parabolic collection lens, i.e. poorer collection angle (> 250.6 mrad in [25]). Because of that, non-intended light clipping as depicted in [Figure 2e](#) (green and black lines missing the collection lens) is enhanced, and as a consequence a fully controlled schlieren effect at the cut-off plane cannot be guaranteed.

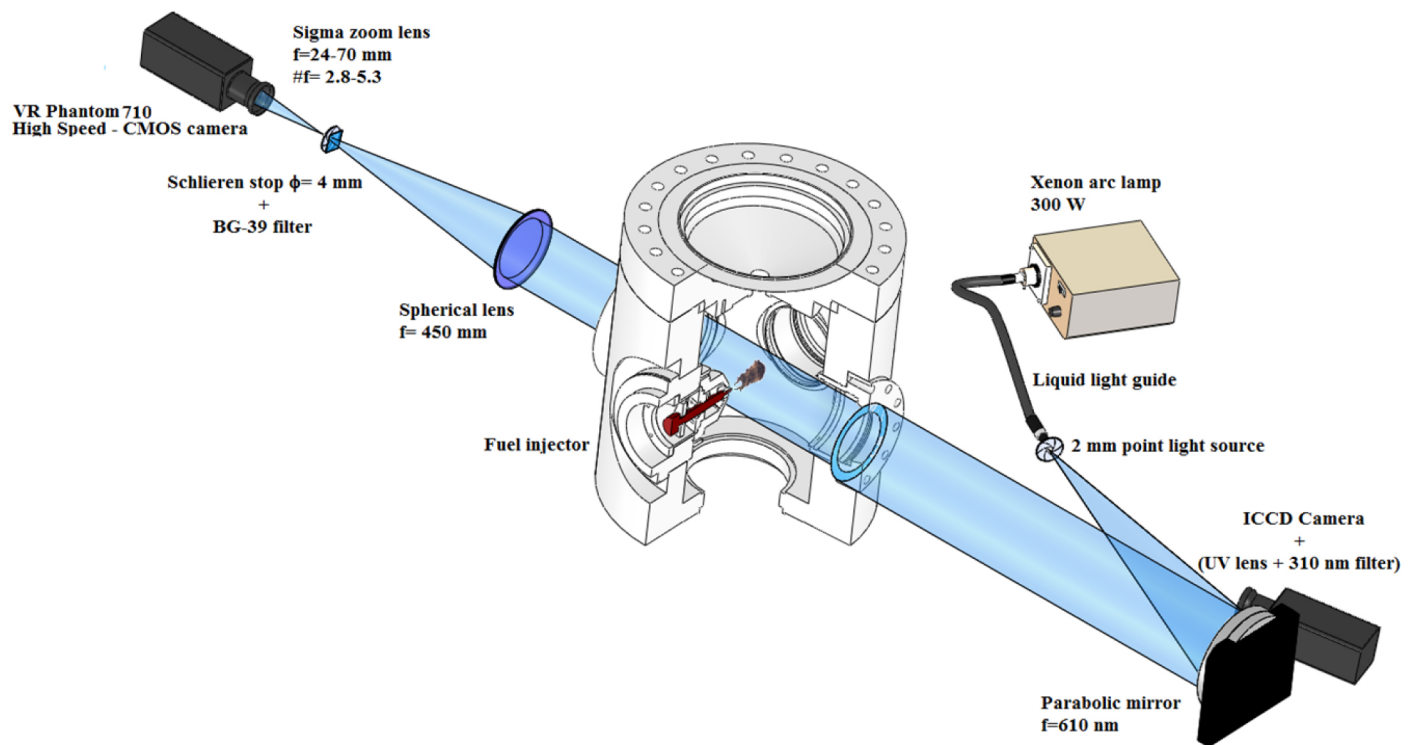


Figure 3. Schematic of the optical set-up for schlieren visualization and OH* imaging.

Table 1. Recording set-up for schlieren imaging and OH chemiluminescence.

	Schlieren Camera	OH* Camera
Frame rate (fps)	42000	1/injection
Exposure time (μ s)	0.3	3000
Start of recording (ms)	0 ASOE	2.3 ASOE
Image resolution (pixel)	544 x 184	512 x 196
mm-pixel ratio	0.297	0.171

Table 1 shows the resulting image size and mm-pixel conversion from the schlieren optical arrangement, as well as the frame rate and exposure time set on the high-speed camera. A second imaging assembly (ICCD camera +UV-lens+ 310 nm filter in Figure 3) was placed with an incidence angle (respect to the spray axial plane) of 13° degrees, to capture the OH* chemiluminescence emitted from the flame, using the camera recording set-up also shown in Table 1.

Schlieren Penetration Processing

Processing routines

Two processing routines were used to extract quantitative information from schlieren images. On the one hand, a purpose-developed code based on a One-Dimensional Loglikelihood Ratio Test (1D LRT) algorithm for segmentation [22] was used for spray penetration measurement. This code statistically determines a threshold digital level value to separate spray and background for every single schlieren image after subtracting a background image, which in the present study is obtained by ensemble-averaging

a set of 30 images recorded before start of injection. The resulting binary image is processed with connectivity algorithms to establish the spray contour, which makes geometrical measurements feasible. The tip penetration is defined as the location of the farthest detected pixel. Initially this code was meant to analyze the liquid length derived from Diffuse Back Illumination technique (DBI), then it was extended to Mie-scattering visualization and recently, it has been shown to be adequate for double-pass schlieren image analysis [26] with relatively short spray lengths (22.5 mm) [24]. Detailed information of this code can be found in [22], which will be referred to in the next sections as LRT code.

On the other hand, an open code for spray penetration measurements proposed by the ECN community has been used for comparison with LRT results. This code was developed by Sandia National Laboratories group and can be found online [27,28]. This method tries to remove the schlieren effect of the hot ambient gases to detect the jet structure [12]. The code is based on the texture that a schlieren image has at any time instant. A derivative process is performed to the image, subtracting the two preceding images I_{t-1} and I_{t-2} . This two-step derivative process highlights the activity zones of the schlieren image, i.e. those pixels that experiment any change because of (i) the spray motion (target measurement) or (ii) background hot-ambient gases motion. This second effect was proven to have no influence on the final result, because of the slow gas velocities on experimental apparatus like the one used on this study (0.2-0.4 m/s). Furthermore, the high-speed frame rates