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Research Paper

Differences between single and double-pass schlieren imaging on diesel vapor spray characteristics

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HIGHLIGHTS

- Vapor spray visualization with single and double-pass schlieren setups is performed.
- Double-pass setup captures more disruptions (gradients) in the background.
- Double-pass system detects higher spray tip penetration in the injection event.
- Decreasing the gas density reduces the discrepancy between optical configurations.
- Double-pass setup produces images with sharper spray contour and more contrast.

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ABSTRACT

The use of schlieren imaging at high acquisition rate has been adopted as a standard optical technique for the analysis of vaporizing diesel sprays under engine-like conditions. A single-pass schlieren arrangement is typically used for the study of axially drilled single-orifice nozzles, as vessels with multiple optical accesses regularly allow line of sight visualization. Contrarily, for multi-spray nozzles, measurements are commonly performed through a single optical access, in which case a double-pass arrangement is employed. As a consequence, the light beams pass through the test section twice, increasing the optical sensitivity of the schlieren setup. However, the influence this has on the macroscopic spray characteristics is still unclear. The scope of this study is to analyze the differences in vapor phase penetration and spreading angle measured for the same injection event, through high-speed imaging, for both single and double-pass schlieren configurations. Experiments were carried out with a three hole nozzle with a nominal orifice diameter of 90 μm, named Spray B from the Engine Combustion Network, using commercially available diesel fuel and in non-reactive conditions. The impact of different injection pressures, chamber temperatures and densities on the spray captured by each setup was assessed. On the results, vapor phase penetration and spreading angle followed the expected trend found in the literature, for the different boundary conditions tested. Comparing the optical setups, vapor phase penetration and spreading angle results obtained with the double-pass arrangement were marginally higher than those from the single-pass. The deviation was observed throughout all tested conditions. For spray tip penetration, although the discrepancy was approximately constant for different injection pressures and chamber temperature, it increased with increasing density. These results highlight the importance of a proper understanding regarding the limitations of optical diagnostics, in particular for results used in calibration of computational models.

1. Introduction

In recent years, the implementation of schlieren imaging in the experimental field has expanded to numerous applications that include military, industrial and scientific research. As Settles [1] stated, it allows seeing optical inhomogeneities in transparent media, like air. In small scale applications, these optical inhomogeneities can relate to density gradients in the medium through which light beams propagate. More specifically, in the field of diesel injection, a schlieren setup, coupled with high-speed cameras and a proper image processing methodology, has become an essential tool for the study of vaporizing diesel sprays.

For many years, researchers have used schlieren imaging to analyze the transient vapor phase of the diesel sprays in both non-reactive and reactive conditions. With this technique it is

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Nomenclature

δ	off axis angle	ECN	Engine Combustion Network
ϵ	angular deflection	ET	energizing time
ψ	inclination angle	P_{inj}	injection pressure
ρ	gas density in the chamber	S	furthest pixel penetration
k_{GD}	Gladstone–Dale constant	S_x	furthest pixel axial penetration
L	optical path length	S_{DP}	double-pass projected penetration
n	refractive index	SOI	start of injection
n_0	refractive index of surroundings	SP	single-pass
DP	double-pass	T	chamber temperature

possible to measure simple macroscopic parameters, like spray tip penetration and spreading angle [2–4], to more complex variables, like ignition delay [5–10] or even lift-off length [11]. It is not only fundamental knowledge to understand how boundary conditions affect these variables, but the experimental data is necessary to validate computational tools, such as 1-D models or computational fluid dynamics (CFD).

The principle of the schlieren application in diesel sprays is simple: the density gradients between the injected fuel and the gas, along the optical path, result in different refractive indexes for the light rays passing through the test section. Subsequently, the boundary between these elements can be depicted, allowing to segment the diesel spray from the background [12]. However, the boundary observed by the schlieren setup is defined by its sensitivity, as each region is determined by the amount of refraction the optical arrangement can capture.

The two most common schlieren configurations are single-pass (SP) [2,8,13–19] and double-pass (DP) [4,20–22]. Typically, the first setup is used for axially drilled single-orifice nozzles, where optical vessels with multiple access allow line of sight visualization. Contrarily, the double-pass setup is commonly used for multi-hole nozzles, where the sprays tend to be visualized through a single optical access. Consequently, the light crosses the test section twice, and the optical sensitivity theoretically increases by a factor of two [1].

Pickett et al. [23] studied the effect of a single-pass system with different spatial sensitivities for spray detection, where two pixel-to-millimeter were compared, but the optical sensitivity was not accounted for. Pastor et al. [12] performed a qualitative comparison of multiple diameters of the diaphragm in the plane of Fourier for a SP setup, thus modifying the optical sensitivity of the singlepass schlieren setup used. However, the comparison presented was for different injection events, and quantitative results of the impact on the macroscopic characteristics of the spray were not presented, as it was not within the scope of their study.

The objective of the present study is to compare two different schlieren imaging setups and their capabilities in the measurement of vapor phase penetration and spreading angle if a diesel spray. Experiments were carried out using a Spray B injector from the Engine Combustion Network (ECN) dataset [24], which is a multi-orifice nozzle in which the three holes are not equally spaced. In consequence, one spray is optically isolated from the others, often referred as the spray of interest. Therefore, it can be visualized both as a single and multi-orifice nozzle for the same injection event. Parametric variations of injection pressure, chamber temperature, and gas density were carried out.

This report is divided into five sections. Followed by this introduction, the experimental facility is briefly mentioned, along with a detailed description of the schlieren principle, optical setups, and image processing methodology. Then, the results are presented, grouped by variations of injection pressure, chamber temperature, and density, with a short discussion of each case. Subsequently, the next part offers a deeper analysis of the results obtained with additional contour data for comparison. In the last section, the main conclusions are drawn.

2. Materials and methods

This section presents the experimental equipment, optical setup, and processing methodology used.

2.1. Test vessel and fuel delivery system

A high pressure and temperature vessel, with three optical accesses, was used. The facility is capable of providing nearly quiescent and steady thermodynamic conditions for experimental spray measurements, relevant to the diesel engine. The test chamber presents constant pressure and flow throughout its section, while a group of compressors, high-pressure reservoirs, and heaters provide the necessary conditions for testing purposes. The facility is explained in more detail in the work of other authors [4,8,25]. The fuel delivery system is made up of commercially available components. A Bosch CP3 pump, powered by an electric engine, supplies high-pressure fuel to a common rail with a pressure regulator driven by a PID controller.

The Spray B nozzle (reference 211200) is thoroughly described in the ECN website [24]. It consists of a three orifice nozzle, where only the spray of interest is studied, which is located at 180° relative to the fuel inlet port. The nozzle outlet diameter is 93.2 μm, with a k-factor of 1.5 [26], and a nominal inclination angle of 17.5°.

2.2. Schlieren principle

Light rays propagate uniformly through homogeneous media, but they are refracted proportional to the refractive index of the medium they are traveling [1]. Gladstone and Dale [27] found that there is a linear relationship between the refractive index and gas density, presented in Eq. (1). Where n is the refractive index, ρ is the gas density, and k_{GD} is the Gladstone-Dale coefficient.

$$n - 1 = k_{GD}\,\rho \tag{1}$$

Additionally, the angular deflection ε of a ray in the perpendicular plane $x - y$, of a light beam that is traveling in a direction z can be obtained by the expression [1]:

$$\varepsilon_x = \frac{L}{n_0}\frac{\partial n}{\partial x}, \quad \varepsilon_y = \frac{L}{n_0}\frac{\partial n}{\partial y} \tag{2}$$

where L represents the optical path length, and n_0 the refractive index of the surroundings. From Eqs. (1) and (2), there is a clear relationship between the changes in density and angular deflection of light rays, that can be visualized through schlieren or shadowgraph imaging. Although both methods are closely related, the use of a cutoff for the refracted light in schlieren systems differen-