

Macroscopic Behavior of Diesel Sprays in the Near-Nozzle Field

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ABSTRACT

The objective of the paper is the characterization of the macroscopic behavior of Diesel sprays by focusing in at the first instants of the injection process at which the spray is clearly affected by the injector needle dynamic.

There are several works dealing with the characterization of Diesel sprays in stationary conditions. Most of them conclude with empirical correlations which predict spray tip penetration as a function of the most important parameters involved in the injection process, such as: injection pressure, gas ambient density, hole diameter and time elapsed from the start of injection. In all these experiments, authors find similar power law dependencies with more or less high level of confidence. Nevertheless, few works have tried to validate or to obtain new correlations for the first instants of the injection process where the spray develops in not stationary conditions because of the influence of injector needle lift.

In this paper, a wide parametrical study based on a zoomed visualization in the nozzle near-field including the first 15 millimeters of the spray has been carried out. The research has permitted the quantification of effects of the main injection parameters on spray tip penetration and spray cone angle at the initial stages of the injection process. From this study, significant differences have been found when comparing results with previous analysis based on sprays in stationary conditions especially in time dependence of spray tip penetration and injection pressure.

INTRODUCTION

The efficiency of combustion and pollution formation of Diesel engine depends on the quality of the fuel-air mixture [1, 2]. In direct injection Diesel engines, where the fuel is injected directly into air, it is necessary to provide adequate conditions for a good macrostructure of the mixture in the combustion chamber. This implies that the injected fuel must be properly distributed in the combustion chamber in an extremely short interval

available for the mixture formation. It is known that the fuel-air mixture process is strongly influenced by the spray behavior, which depends on several parameters. These parameters can be classified into two groups: parameters related to the diesel injection system and parameters related to the environment where the spray is injected. Although there are several works dealing with the characterization of diesel sprays in stationary conditions [2-6], only in few works in the current literature the authors have tried to obtain new correlations focused in the first millimeters of spray [7-9]. Considering the fact that, in this type of engines, the characteristic length for spray development is around 25 mm. So, it would be interesting to know how the spray behaves in such particular conditions.

In this work, a parametrical study based on a zoomed visualization in the nozzle near-field including the first 15 millimeters of the spray has been carried out. In the study, the macroscopic spray characteristics of a six-hole nozzle assembled in a solenoid injector holder have been characterized in a nitrogen pressurized test rig in non evaporative conditions (room temperature) and thus avoiding fuel evaporation.

An extensive test matrix has been used using different values of injection pressure and density in the chamber. From experimental data, spray tip penetration and spray cone angle have been characterized. The analysis of the results have permitted to quantify the dependencies of the involved parameters on the spray characteristics in order to determine to what extent can the dependencies of the involved parameters on spray tip penetration in stationary conditions be extrapolated to a non-stationary spray.

The paper is structured in five sections. First of all, a review of previous works available in the literature about Diesel spray behavior is presented. After that, the experimental facilities are described in the second section, basically the nitrogen test rig where the visualization study has been done. Image acquisition system and post-processing software are also described in this section. The third section includes a description of experimental procedure, introducing the test matrix used for this study. In section four, the results obtained are

presented, and finally in section five the analysis of them is carried out.

BACKGROUND

Due to its great influence on the combustion efficiency, the spray behavior has been the subject of several experimental and theoretical works for a long time and intensive investigations are still underway by many researchers. Most of these investigations conclude with empirical or semi-empirical laws, which predict the penetration as a function of several parameters. In this way, the work of Hay and Jones [3] includes a critical revision on the correlations available in the literature proposed for Diesel sprays, and concludes that the best ones are those proposed by Dent [4] and Wakuri et al. [5]. Later, Hiroyasu and Arai [2] proposed a different penetration law divided in two regions: before and after the break-up time. More recently, Naber and Siebers [10] derived a penetration correlation for non-vaporizing spray which follows the spray penetration analyses of Wakuri et al. but including significant contributions in order to estimate the arbitrary constant that normally appears in the penetration correlation. Also, Desantes et al. [6], using axi-symmetrical nozzles with different diameters, proposed a correlation where exponents affecting each parameter are consistent with previous experimental research in diesel sprays at high ambient density.

All these above mentioned correlations involve the same parameters (ΔP , ϕ_o , ρ_a , t) with more or less the same weights. The dependencies of these variables can be obtained just performing a dimensional analysis of the following variables: ambient gas density (ρ_a), time elapsed from the start of the injection (t) and the

instantaneous momentum flux ($\dot{M}_o$) through the orifice [6]. This theoretical analysis leads to spray tip penetration expression which shows the following dependencies:

$$S(t) \propto \rho_a^{-1/4} \cdot \Delta P^{1/4} \cdot \phi_o^{1/2} \cdot t^{1/2} \quad (1)$$

which have been corroborated experimentally in most of the works cited above.

Desantes et al. [11,12] developed and validated a theoretical model for diesel spray penetration including a new correlation of penetration as a function of spray momentum flux. They obtained the following expression:

$$S(t) = 1.26 \cdot \dot{M}_o^{1/4} \cdot \rho_a^{-1/4} \cdot t^{1/2} \cdot \tan^{-1/2} \left(\frac{\theta}{2} \right) \quad (2)$$

Taking into account that momentum flux is given by

$$\dot{M}_o = \dot{m}_f \cdot U_o = \rho_f \cdot \frac{\pi}{4} \cdot \phi_o^2 \cdot U_o^2 \quad (3)$$

and applying Bernoulli equation through the nozzle hole, and expression equal to equation (1) is obtained.

Nevertheless, correlations obtained for spray tip penetration which follow tendencies as equation (1) are valid only for instants, t , higher than a *transition time*, t_t . This *transition time* has been referred in different ways in some works in the literature. Therefore, for example, Hiroyasu and Arai [2] proposed a transition time, called *break-up time* at which there is a change from a linear dependence on time of penetration to square root dependence. Nevertheless, for Naber and Siebers [10] the transition time is the instant when the spray changes from being dominated by injected liquid to being dominated by entrained gas. Finally, in Desantes et al. [6] the time elapsed from the start of the injection to the transition time was identified with the time interval during which the mass flow rate (or more generally momentum flux) is still increasing due to the needle lift. In this time interval, the authors verified a linear dependence of time on the spray tip penetration, but nevertheless the available data was not enough to obtain a correlation representative of the first millimeters of the spray. For this reason, the objective of this study is to obtain an experimental law in order to predict the spray tip penetration as a function of the representative variables but focused at the initial stages of the spray where injection conditions are clearly not stationary.

EXPERIMENTAL FACILITIES

NITROGEN TEST RIG

For the macroscopic spray characterization, an injection test rig is used that reproduces both the high gas density and pressure encountered in a Diesel engine combustion chamber. The test rig is pressurized with nitrogen and it basically consists of a steel cube, including a chamber machined inside it. There are optical accesses in 3 of the cube faces and so allowing different configurations for flashes and camera. The test rig is designed for a maximum gas pressure of 6 MPa. It is necessary to circulate the nitrogen through the rig because otherwise the injected diesel would obscure the windows and severely degrade the quality of the images. Temperature can be controlled in a range between 15 and 60 °C. The test rig allows all the conditions in the chamber to be constant for each experiment. Camera and flash emplacement can be adapted depending of the necessities of the experiment. In Figure 1 a photograph of the nitrogen test rig is presented.

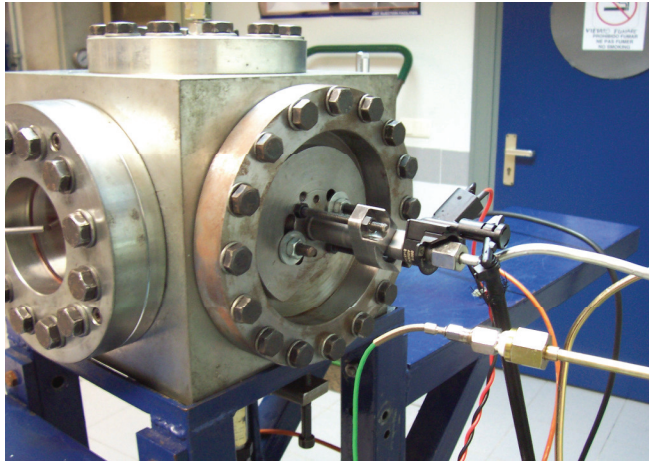


Figure 1. Nitrogen test rig.

IMAGE ADQUISITION SYSTEM AND IMAGE PROCESSING SOFTWARE

Images are taken with a 16-bit CCD camera (SensiCam by PCO). The spatial resolution allowed for this camera is 1280x1024 pixels, with an exposure time up to 5 microseconds. High power xenon flash is used for a proper illumination.

The camera is located in the opposite face of the injector and two flashes are used for lateral illumination, both facing each other providing a uniform illumination in the chamber.

Because of camera velocity limitations, each image corresponds to a different injection process. The injection and its synchronization with the camera and flash are managed by a purpose-built electronic system using the injector trigger signal as the reference to take images. This system allows working at very low injection frequencies. The high time interval between injections is required for the N_2 flow to eliminate the fuel droplets from the previous injection and thus maintain good optical access to the spray.

Special software is used for image processing. The segmentation algorithm is based on the log-likelihood ratio test (LRT). This method is especially indicated when boundaries definition is difficult to do, as in the case of Diesel spray images. Moreover, the method proved to be almost insensitive to intensity fluctuations between pictures, providing better results than other algorithms. The influence of illumination quality was also evaluated in specific tests. Results demonstrated that the algorithm properly detects the estimated spray boundaries even in the case of comparatively poor illumination. Details of the image processing software are available in [13].

INJECTION SYSTEM

A complete conventional common rail injection system [14] was used to generate Diesel sprays in the nitrogen test rig. It includes a high pressure volumetric pump driven by a motor, the rail, solenoid injector as well as an electronic system to govern injection process.

The injector used for these experiments has a standard solenoid valve actuator, assembled with a 6-holes cylindrical nozzle. The outlet diameter of the holes is 150 μm . The angle between the sprays and the plane of the camera is 15°, as seen in Figure 2.

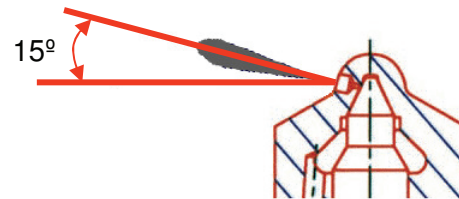


Figure 2. Spray elevation angle.

EXPERIMENTAL PROCEDURE AND CONDITIONS

For the visualization different injection conditions have been tested. Five injection pressures of 30, 50, 80, 130 and 180 MPa were used. For each pressure, three different values of back pressure were used: 2, 4 and 6 MPa which considering a constant temperature inside the test rig of 25 °C, provide three different values of air density: 22.6 kg/m³, 45.2 kg/m³ and 67.8 kg/m³. The values of the different test parameters considered are summarized in Table 1.

Injection Pressure [MPa]	Back Pressure [MPa]	Density [Kg/m ³]
30	2	22,6
	4	45,2
	6	67,8
50	2	22,6
	4	45,2
	6	67,8
80	2	22,6
	4	45,2
	6	67,8
130	2	22,6
	4	45,2
	6	67,8
180	2	22,6
	4	45,2
	6	67,8

Table 1. Experimental conditions for the visualization.