Experimental Characterization of a Fuel Direct Injector Spray Aiming to Improve Engine Design

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ABSTRACT

The constant evolution of environmental legislation has pushed the automotive industry to reduce the air pollutant emissions from motor vehicles. Fuel direct injection has emerged as an effective strategy to minimize the exhaust emissions from internal combustion engines, enabling precise control of the fuel atomization process inside the combustion chamber and a reduction of knock occurrence due to optimized fuel evaporation. In order to reach these goals, a precise design of a fuel direct injection system generally requires a series of computational studies that often demand algebraic correlations between spray and injection parameters. These correlations may not be simple and, as such, it is challenging to use them to characterize specific injectors sprays, a topic that still lacks a deeper technical and scientific examination in literature. In that regard, the objective of this paper is to investigate the spray of a direct injector to correlate its operational parameters with the injection parameters. The studied spray operational parameters are the cone angle and penetration, while the injection parameter herein analyzed is the injection pressure. These correlations provide necessary inputs to the design of more efficient engines.

INTRODUCTION

Fuel direct injection has been identified as an effective strategy to minimize the exhaust emissions from internal combustion engines [1] [2] [3]. The design of these injection systems requires the characterization of the fuel spray, interest of many studies [4] [5] [6]. Many variables impact the spray behavior, such as the injector geometry, the injection conditions, the fuel mechanical properties and the conditions inside the combustion chamber. Furthermore, various spray characteristics are relevant to an optimized injection system, for example its structure, its droplets characteristics and its macroscopical configuration. [7]. This paper will study the influence of the injection pressure, an injection condition, on the spray cone angle and penetration, two relevant macroscopical spray variables. Figure 1 [8] illustrates a fuel spray. Cone angle, that is defined as the angular amplitude of the spray, varies with the distance of injector orifice and so can be measured at a given distance, as an average or in function of distance. Penetration is the distance normal to the plane of the injector reached by the spray at a given time. Penetration can also designate the maximum distance achieved by the spray. [8]

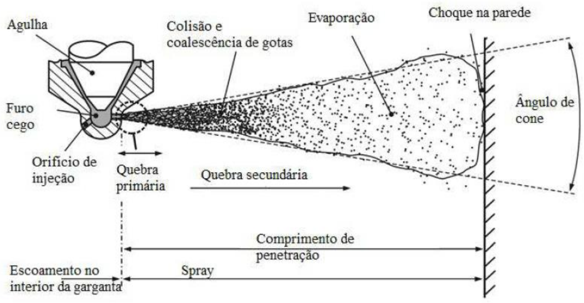

Figure 1. Fuel spray representation [8]

EXPERIMENTAL SETUP AND PROCEDURE

Experimental setup can be divided in three systems: the pressure system, the electronical system and the optical system.

PRESSURE SYSTEM - Pressure system controls the injection pressure and stores experimental fluid. The experimental fluid used is Exssol D40, a fluid with physical properties similar to ethanol but less flammable. A nitrogen cylinder is used as pressure supplier. A pressure manometer JETCONTROL *600* is used to set the injection pressure. The manometer is connected to a fluid reservoir that also acts as a pressure vessel. The reservoir is connected to the injector, that injects the fluid in the atmosphere producing the spray. A Bosch HDEV 5.1 fuel injector is characterized on the present paper. Figure 2 illustrate the pressure system.

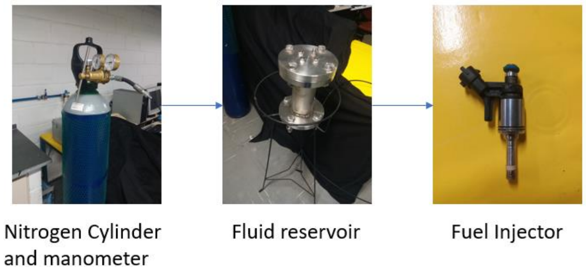

Figure 2. Pressure System

ELECTRONICAL SYSTEM - The Electronical system function is to operate the injector. A computer runs a software the controls a Engine control unit (ECU) model MoTec M4, that provide a precise control of the injection frequency and duration. Spray frequency is set to 12,5 hz and spray duration is set to 5 ms. The control unit generates a signal that is limited by a low pass circuit. A Driver Pick and Hold GDI Magneti Mareli treats the signal to a shape that can trigger the injector, based on the injector specifications of peak current e duration. Figure 3 illustrate the electronical system.

Figure 3. Electronical System

OPTICAL SYSTEM AND IMAGE ACQUISITION - Optical system acquires the spray images using shadowgraph technique. A led lamp and a light diffuser provide a bright background so that a Phanton high speed camera can visualize the spray. Figure 4 illustrates the optical system as well as shadowgraph methodology. The camera acquisition frequency was set to 2500 hz and the exposure time to 300 µs.

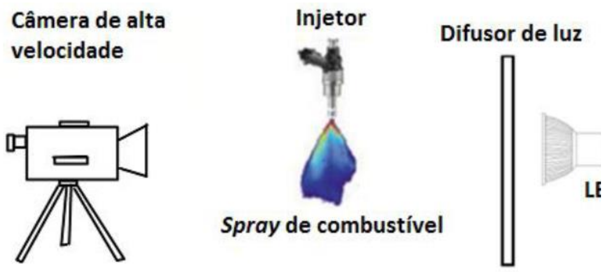

Figure 4. Optical System

IMAGE TREATMENT - The acquired images were treated and analyzed following methodologies proposed by GUZZO [9][10]. Treatment removes elements other than spray and enhances contrast in other to make spray boundaries easier to detect. The images containing the spray are subtracted from a base image of the nozzle before injection. Next a median filter is applied to remove noise from the images, so it is not captured by the software as an edge. Finally, the image pixels values are brought to the max range of a black and white image, from 0 to 255.

Then each image is loaded, the coordinates of the tip of the nozzle are entered and scanning begins from there in polar coordinates at increasing distances from the nozzle detecting variations bigger than a threshold to detect the edge. The referenced analyzes provide cone angle in function of distance from injector orifice and injection pressure and the penetration in function of time since injection and injection pressure. Both these variables are calculated as a mean of 9 different sprays for each image.

RESULTS AND DISCUSSION

Figure 5 presents one of the spray images recorded for 25 bar injection pressure. Figures 6 shows those same images after treatment.

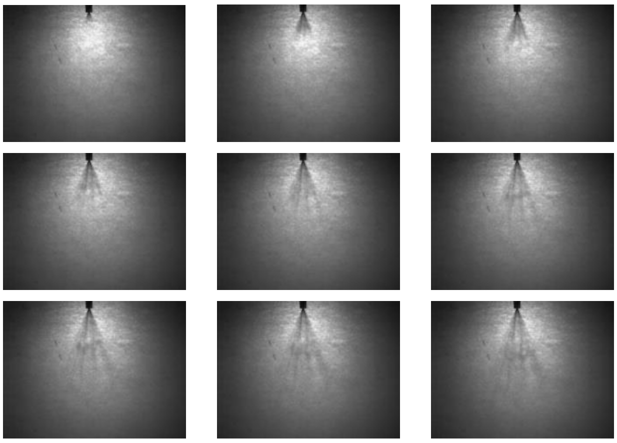

Figure 5. Untreated spray images

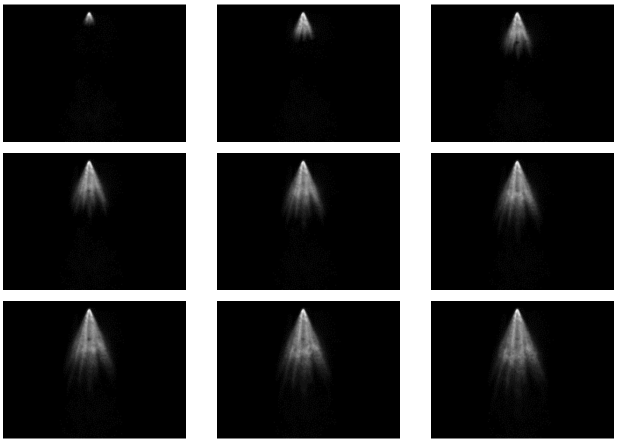

Figure 6. Treated spray images

Analyzing figures 5 and 6 it is possible to notice the effect of the treatment. Background elements and noise are successfully removed while preserving spray information and shape. Figure 7 shows the detected cone borders (white dots) of a specific for 25 bar injection pressure.

Figure 7. Spray border detected

The detected border is consistent with the spray border in the analyzed region, 5 to 15 mm from injector nozzle. For greater distances the spray becomes thinner, and the detected border diverges. This supports the cone angle analysis results. Figure 8 and 9 presents the cone angle analysis results relative to the distances from the injector nozzle for injection pressures of 25 and 50 bar, respectfully. The mean value as well as its superior and inferior bounds are presented. The shape of the presented curves as well as it's general values are noticeably similar. The variance of the acquired data almost makes two curves coincident. It can be implied that the influence of the injection pressure on the cone angle is almost negligible for the analyzed injector and within the analyzed pressure range.

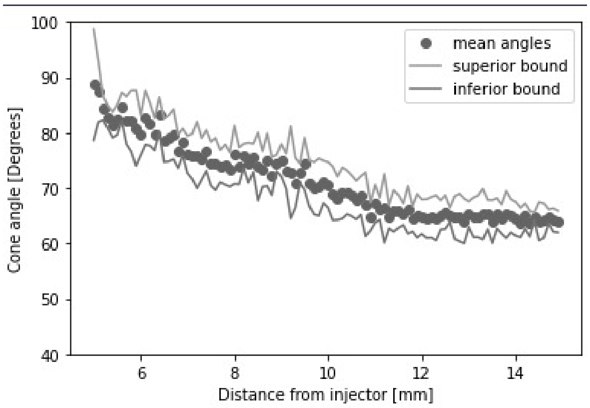

Figure 8. Cone angle for injection pressure of 25 bar

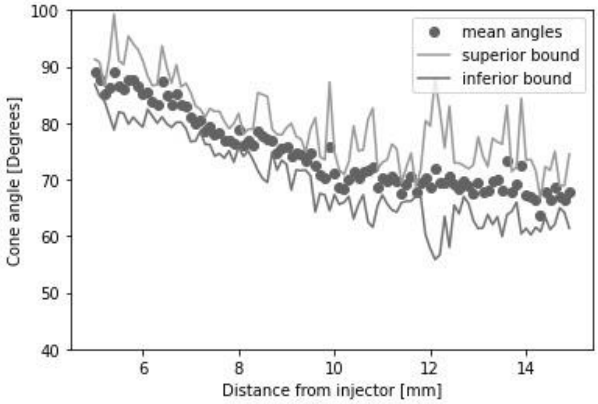

Figure 9. Cone angle for injection pressure of 50 bar

The development of the cone angle with distance of the injection nozzle shows that it decreases as distance increases. That can be attributed to the influence of the air resistance. Figures 10 and 11 present the penetration of the spray in function of time since the injection for injection pressures of 25 and 50 bar. Analyzing the acquired data, it is noticeable a greater penetration for the 25 bar injection time spray on the first frames analyzed, starting with roughly 90 pixels against 70 of the 50 bar, meanwhile on later frames the 50 bar injection time features greater penetrations. This behavior can be explained by the lack of synchronization of camera and spray injector. Every spray injection lasts for about 13 to 14 frames, but the time of the spray each frame captures is slightly different inside a given range.

If the variation of penetration is compared, the 50 bar injection pressure shows slightly greater values though almost the entire range of analysis. This shows a limited influence of injection pressure on spray penetration. This behavior is explained by the influence of the injection pressure on the initial spray droplets speed. The error margin is bigger overall for the 25 bar spray and grows in later frames as its bottom edge becomes less clear while the spray produced under 50 bar has a more uniform and consistent bottom edge that penetrates faster and therefore is better detected.

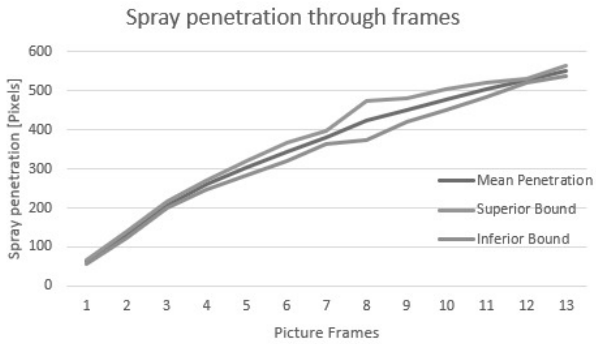

Figure 10. Spray penetration per image frame at 25 bar pression

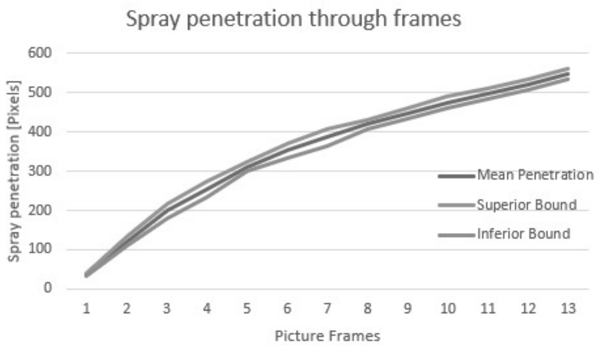

Figure 11. Spray penetration per image frame ar 50 bar pression

CONCLUSION

This paper analyzed the influence of the injection pressure over the spray cone angle and penetration. The experiments conducted allowed the visualization of the spray, as well as the methodologies applied made possible the delectation of spray borders. The image treatments used allowed for clear images and made possible detection of the spray edge for a good range beyond the injector nozzle.

Observing the information obtained, it is possible to conclude that the injection pressure has low influence on the cone angle through the distance from the injector nozzle, being the difference not significant compared with the error margin, while it is possible to see its influence on spray penetration.

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