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Research Paper

Study of liquid and vapor phase behavior on Diesel sprays for heavy duty engine nozzles

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HIGHLIGHTS

- 2 Nozzles for heavy duty were studied in non-evaporative and evaporative conditions.
- Differences on spray shape were found between cold and vaporizing conditions.
- Large values of Liquid Length were obtained for the studied nozzles.
- For vapor spray, big nozzle diameter will lead longer transition time.

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ABSTRACT

A lot of effort has been put in the past years into the understanding of the delivery and development of diesel sprays in engine-like conditions as it has been proved to be a very important step for the design of better and cleaner commercial engines. Due to the bigger share of passenger cars engines over heavy duty engines, the research has been mainly focused on the investigation using small nozzles. This paper studies two nozzles with diameters representative of those that can be encountered in heavy duty engines, with the objective of corroborating the conclusions gathered for small nozzles representative of passenger car engines. The experimental data have been acquired by state-of-the-art techniques and equipment, and serves two purposes: further the understanding of the physics involved in the injection event and spray evaporation; and provide a dataset to CFD models that can accurately predict the behavior of the injection event.

The tests were performed in a constant pressure flow vessel that allows to simulate engine-like conditions (1000 K and 15 Mpa) with continuous flow. The injection system tested is a novel, common-rail, solenoid-actuated injector for heavy duty applications which operates up to 220 Mpa. All experiments were performed in non-reacting conditions. The extended test matrix allowed to determine the influence of several parameters such as rail pressure, gas temperature, gas density, and nozzle geometry on the air–fuel mixing and evaporation process, by analyzing the spray penetration and spreading angle. Mie scattering and double-pass Schlieren optical configurations have been used to measure global liquid and vapor penetration, respectively.

The data proves that spray penetration at low temperature can be up to 15% faster than spray penetration at high temperature conditions at the same density for the nozzles experimented, which limits the usability of low temperature experiments to infer the behavior of the injector at high temperature conditions. The data also shows that the nozzle with the biggest diameter provided the highest value of stabilized liquid length as expected. Also, when vapor phase is reached, the temperature has negligible effect on the global diesel spray morphology, and no influence on the tip penetration or on the spreading angle.

1. Introduction

Energy consumption and emissions production from internal combustion engines remains the two most important key factors in the design and development of engines [1,2]. The harmful effect of the exhaust gases to the ambient and public health resulting from the combustion, combined with the limited amount of available energy, create the need to limit, as heavily as possible, the level of pollution and CO_2 that engines are allowed to produce [3]. The increasingly demanding emission regulations creates a tough challenge to researchers working in the engines industry

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Nomenclature

S	penetration	CPFR	Constant Pressure Flow Rig
D194	194 μm nozzle	Xe-arc	Xenon arc
D228	228 μm nozzle	ΔP	pressure drop between inlet and outlet
HPHT	High Pressure High Temperature	ρ_a	density of the ambient gas
PID	Proportional Integrative Derivative	ρ_f	density of the fuel
CMOS	Complementary Metal-Oxide Seminconductor	C_a	area coefficient
ASoI	After Start of Injection	C_v	velocity coefficient
ASoE	After Start of Energizing	T_{gas}	temperature of the ambient gas
ID	Ignition Delay	D_0	outlet diameter of nozzle
LOL	Lift Off Length	θ	spray plume cone angle
LL	Liquid Length	t_r	transition time

to provide advanced combustion solutions that can comply with the normative. The effort dedicated to research on the field of diesel engines has been, and still is, very large.

In the particular case of off-road heavy duty diesel engines, the emission regulations have been less stringent than those of the light duty engines, therefore the efforts for improvements and the amount of research for this application is not as numerous [4,5]. Nevertheless, the recent legislation for heavy duty applications on behalf of reducing fuel consumption and pollutant emissions have pushed the industry to develop new technologies and combustion strategies that address those concerns and challenges.

Most of the recent topics of research in the engine community are being performed mainly for downsized engine type specifications with very small nozzle diameters (80–100 μm), in order to understand how the nozzle geometry influences the diesel injection process and spray development. One example is the Engine Combustion Network [6–8]. Those studies also involve the development of numerical models, either based on physical assumptions or simply interpolating experimental data. However, regarding bigger nozzle diameters the up-to-date information available is limited. Most of the documentation available focused on diesel injection processes for nozzles with relatively big diameters was written one or two decades ago, when the injector technology reached lower injection pressure levels, the actuating systems had a different performance, and the experimental equipment were not as good as the optical and electronic devices that are used nowadays. For instance, Naber and Siebers [9] in 1996, studied the ambient gas density and fuel vaporization effects on diesel spray penetration and dispersion using big size nozzles of about 198–340 μm, reaching injection pressure levels of about 150 MPa. Later in 1999, Siebers [10] studied the effects that the most important parameters have in the liquid phase penetration and cone angle and developed a theoretical scaling law that was adjusted by means of intensive experimental campaigns. Siebers [10] found a linear dependence of liquid length on orifice diameter, a relevant and non-linear inverse effect of the gas temperature on liquid length and an insignificant effect of injection pressure. The test matrix performed by Siebers [10] included an extensive range of nozzle diameters from 100 to 498 μm, densities and temperatures. Undoubtedly, they found significant results; however, the maximum pressure drop in the orifice was about 170 MPa and only the liquid phase was studied.

Considering the aforementioned facts, this research is carried out in order to develop a better understanding of the effect of big nozzle diameters on the atomization and evaporative performance of the spray using up-to-date injection system technology and optical devices, measuring the liquid phase and vapor phase penetration of the fuel spray in engine like conditions. Therefore, in this paper, two different diesel nozzles conceived for medium/heavy duty engine operation have been investigated at different ambient temperatures and gas densities similar to those that the injected spray would encounter in the combustion chamber.

The paper starts describing the experimental set-up and methodologies; first by presenting the nozzles and injection systems, along with the High Pressure and High Temperature constant pressure test rig, and followed by the description of the different optical techniques and image processing methodology employed. In the next section, the main results obtained are presented and discussed, the results from this section are then used to create empirical correlations that can describe the behavior of the different variables investigated. To finalize, the last section underlies the main conclusions gathered throughout the work.

2. Methodology

2.1. Nozzles and injection system

Two similar nozzles with convergent holes have been experimented in this study, which are representative of nozzles for medium/heavy duty engines. Table 1 shows the basic characteristics of the nozzles. Both nozzles have the same orifice length size of 920 μm and different outlet diameter. Given the L/D ratio (nozzle length divided by the outlet diameter) the likelihood of cavitating operation is increasing from the D194 to the D228 nozzle [11]. The nozzles are coupled to a common rail type fuel injector with a solenoid type actuation, typical for heavy duty application engines.

The injection system comprises a low pressure pump, a high pressure pump, a common rail regulated with a PID controller and all the necessary high pressure lines and filters for accurate operation. The high pressure pump consists on an electrically driven pump able to reach more than 220 MPa injection pressure and is fed via the low pressure pump. The PID controller actuates opening or closing the common rail in order to achieve the injection pressure desired. Injection pressure is measured with a Kistler pressure sensor directly connected on the common rail. A refrigeration circuit is also employed to avoid overheating of the fuel and the high pressure pump of the injection system.

2.2. The high pressure high temperature test rig

The different experimental techniques described in the next sections have been performed in a high pressure high temperature

Table 1
Nozzles used in the study.

Nozzle	Diameter (μm)	L/D
D194	194.4	4.73
D228	228.8	4.02