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Experimental investigation of the effect of orifices inclination angle in multihole diesel injector nozzles. Part 2 – Spray characteristics

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ABSTRACT

Diesel spray development is a key research topic due to its impact on the combustion characteristics. On the current paper, the effect of the orifices inclination angle on the spray penetration characteristics is evaluated. For this purpose, three nozzles with included angles of 90, 140 and 155° are selected. Visualization tests are performed on a room-temperature constant-pressure vessel pressurized with a high-density gas (SF_6), in order to reproduce the density conditions inside the combustion chamber at the start of the injection event. Both frontal and lateral Mie-scattering visualization are used, depending on the particular nozzle configuration. Results show how the spray penetration is slower as the inclination angle increases, which is linked to its lower nozzle outlet velocity. A statistical correlation of the spray penetration as a function of the area and velocity coefficients is obtained and discussed.

1. Introduction

Many researchers have focused on the study of diesel spray characteristics over the last decades. Naber and Siebers [1] established that the inert spray penetration has two different stages: an initial one, where the spray penetration grows linearly with the time; and a second one characterized by a square-root temporal evolution. Payri et al. [2] showed a similar behavior, and related the transitional time between both stages to the moment at which the injection rate stops being affected by the needle position. On the contrary, Zhang and Hung [3] analyzed the transitional time as a combined function of inertial, viscous and surface tension forces. More recently, Kostas et al. [4] and Li and Xu [5] proposed that the experimental trend of the spray penetration before this transitional time was actually proportional to $t^{3/2}$ once the very first millimeters of the spray were properly captured.

Additionally, spray penetration is significantly dependent on the nozzle orifice geometry. Payri et al. [6] reported a higher spray penetration for a tapered orifice compared to a cylindrical one, linked to its higher effective outlet velocity. Boggavarapu and Ravikrishna [7] showed that enlarging the orifice inlet rounding radii was also effective to increase the tip penetration velocity. Both these effects are related to the increase of the spray momentum, which has been seen as the most important parameter to characterize the spray penetration [8]. The needle seat geometry has also shown a significant impact on the spray [9]. Another important aspect is the ambient density, which tends to reduce spray tip velocity due to the combined effect of higher aerodynamic forces and a wider spray angle [10,11]. Eventually, the combination of high ambient density with ultra-high injection pressure may lead to the detection of shock wave phenomena in the spray tip area, affecting also the spray behavior [12,13]. Spray penetration is also affected by the fuel physical properties, mainly density, viscosity and surface tension [14–16].

Apart from the characteristics of spray penetration, it is important to take into account also the structure of the spray itself [17–19]. During its first stages, especially in high density conditions, the spray develops a mushroom-like structure due to the interaction of the liquid fuel with the ambient gas [19,20]. As the spray develops, its structure transitions to a nearly conical shape, where the spray angle can be defined, followed by a semi-spherical tip. A high resolution analysis of the first millimeters of the spray shows that in reality there is a transitional region until reaching the spray angle [21–23]. X-ray visualization techniques have allowed to obtained the mass fraction radial distribution inside the spray [24–26], characterized by similar Gaussian profiles to those typical of gas jets [24,27]. When the spray is injected into evaporative (high temperature) conditions, it has to be considered also that full spray evaporation is reached after a certain distance from the nozzle tip. This distance is called stabilized liquid length, and depends mostly on the orifice effective outlet diameter, the spray angle, the fuel properties and the ambient temperature [28–32].

Significant effort has been also made in the modeling of diesel sprays [33–36]. One-dimensional phenomenological models, based on the gaseous jet analogy, have shown to be useful to evaluate the main

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Nomenclature

a–d	coefficients for the spray penetration correlation
A_{eff}	effective area
A_o	geometrical area
C_a	area coefficient
C_d	discharge coefficient
C_v	velocity coefficient
D_o	geometrical nozzle diameter
k	constant term for spray penetration correlations
K_u	spray velocity constant
$\dot{m}$	mass flow
$\dot{M}$	momentum flux
P_b	discharge pressure
P_i	injection pressure
S	spray penetration
S'	spray penetration from image contour
t	time after start of injection
u_{eff}	outlet orifice effective velocity
u_{th}	theoretical outlet orifice velocity, $u_{th} = \sqrt{\frac{2\cdot(P_i - P_b)}{\rho_f}}$

Greek symbols

α	nozzle included angle
ΔP	pressure drop, $\Delta P = P_i - P_b$
ρ_a	ambient density
ρ_f	fuel density
υ_f	fuel kinematic viscosity
θ_u	spray angle defined from the velocity profile

spray features both in stationary and transient conditions [37,38]. Nevertheless, microscopic details of the spray such as the droplet velocity and diameter or the turbulence characteristics cannot be evaluated using these methodologies. For this reason, full Computational Fluid-Dynamic (CFD) tools have been developed. Most of the available models have been based on Reynold-Averaged Navier-Stokes equations (RANS), which use simplified turbulence models able to capture only the average spray behavior [39–42]. In the last years, more advanced methodologies based on Large Eddy Simulation (LES) or Direct Numerical Simulation (DNS), capable to capture also spray cyclic oscillations, have also been investigated [43–45].

In the current paper, an investigation of the effect of nozzle inclination angle on the spray characteristics is performed. For this purpose, three multi-hole nozzles with different included angle are assessed. The nozzles were previously evaluated from the point of view of their hydraulic performance in terms of mass flow and momentum flux [46]. Spray penetration is obtained based on lateral and frontal Mie-scattering visualization. Results show that spray penetration is slightly faster as the included angle decreases. Additionally, a correlation of the spray penetration based on the area and velocity coefficients is obtained.

As far as the structure of the paper is concerned, the work is divided in 5 sections. Section 2 describes the experimental arrangement, including an uncertainty analysis as a function of the included angle for the frontal visualization. The main spray penetration results are depicted in Section 3. A theoretical analysis of the spray penetration is performed in Section 4, leading to the generation of a statistical correlation for the experimental data available. Finally, the main conclusions of the study are drawn in Section 5.

2. Experimental setup

2.1. Nozzles

In the current paper, three fuel nozzles with included angle values of the included angle $\alpha = 90$ (N1), $\alpha = 140$ (N2) and $\alpha = 155°$ (N3) have been used. These nozzles are equal from the point of view of the number of holes (10), nominal outlet diameter ($D_o = 0.09$ mm), conicity (*k-factor* = 1.5) and hydrogrinding level (10%), and are mounted on a solenoid-driven fuel injector. This injector is connected to a custom-made common-rail system capable to reach up to 200 MPa of injection pressure

2.2. Spray visualization

Spray visualization tests have been performed at room temperature on a constant-pressure test rig capable to reach up to 0.8 MPa. In order to work with ambient densities similar to those characteristic of the combustion chamber in a diesel engine, the test rig is filled with a gas denser than air. In particular, sulphur hexafluoride (SF_6) has been used. This gas is provided to the test rig by a roots compressor with a nominal flow velocity of 3 m/s, enough to facilitate the dragging of the fuel droplets from one injection cycle to another without impairing spray penetration.

As stated before, SF_6 was selected as the working gas in order to match the desired chamber density at pressure levels acceptable for the test rig (which are lower than the standard engine conditions). It has to be highlighted that this could have an effect on the nozzle flow characteristics due to the different pressure drop across the nozzle. This

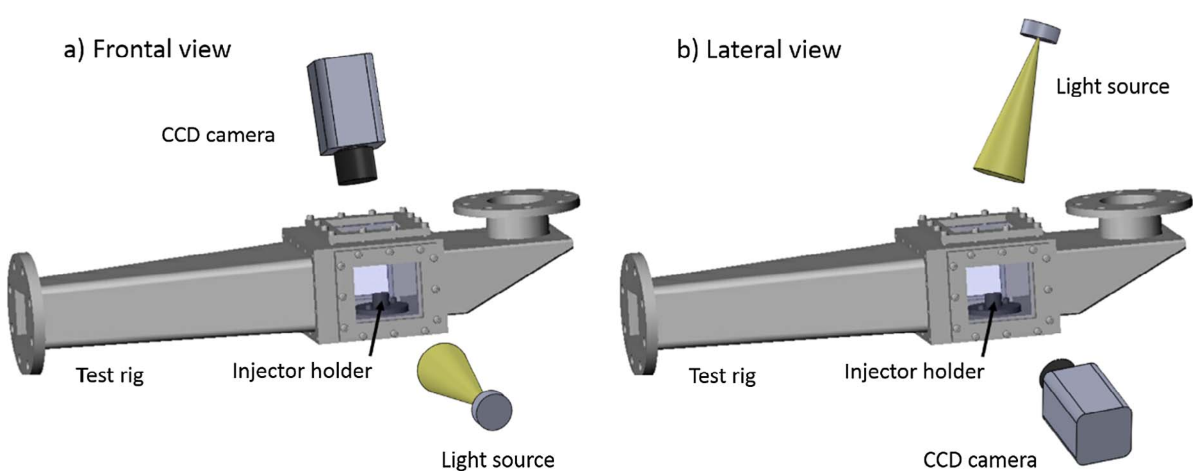

Fig. 1. Schematic of visualization configurations: a) frontal view; b) lateral view.

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