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Study of new prototype pintle injectors for diesel engine application

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A new prototype common rail injector featuring a complete new nozzle design concept was exhaustively characterized both from the hydraulic and spray formation point of view. A commercial injection rate meter together with a spray momentum test rig were used to determine the flow characteristics at the nozzle exit. A novel high pressure and high temperature chamber (up to 15 MPa and 1000 K) was used to determine liquid length and vapor penetration. Using these tools, three different pintle nozzle designs, with specific features in the outlet section, were studied. The test matrix included a sweep of injection pressure up to 2000 bar and a sweep of ambient temperature up to 950 K. The results obtained show that pintle nozzles offer great potential in terms of fuel mass flux controlled by variable nozzle geometry. Effects in the hydraulic measurements and spray images due to the variable geometry were observed and characterized.

1. Introduction

On diesel engines, the combustion process is significantly driven by the performance of the fuel injection system. For this reason, the characteristics of fuel injectors and their impact on spray formation and engine performance have been widely studied in the literature. Sun et al. [1] showed that the geometrical details of the fuel injector nozzle holes affect its internal flow characteristics, including the formation of cavitation. Jiang et al. [2] analyzed that the flow conditions inside the nozzle also significantly linked to the physical properties of the fuel, especially to the viscosity. Salvador et al. [3] found through CFD simulations that while the flow characteristics are a direct function of the nozzle hole geometry when the injector arrives to stabilized conditions, during the first stages of the injection the flow is strongly affected by the position of the needle itself. Similar result was obtained experimentally by Viera et al. [4] using a direct-acting piezoelectric injector, which showed that the injection velocity was affected by the needle lift up to approximately 50–70 μm, depending on the injection pressure level. Dumouchel [5] reviewed the different factors affecting the spray atomization process, showing that it is improved by increases in the nozzle outlet velocity and by the appearance of cavitation inside it. Payri et al. [6] used a high magnification visualization technique to study the spray formation in the near-nozzle field, concluding that the nozzle effective outlet area and velocity enhance the spray opening angle and the primary atomization characteristics. Salvador et al. [7] used a 1D spray model, based on the analogy of the liquid spray to a gas jet, to show that the local distribution of equivalence ratio is directly linked to the spray velocity and the non-dimensional Schmidt number, which depends on the fuel and discharge ambient physical properties. As a consequence, combustion efficiency and soot emissions are also impacted by the injection characteristics [8].

On realistic engine conditions, the spray outlet velocity (and, consequently, the spray formation characteristics) has a transient evolution depending on the needle dynamics [9]. As stated before, high injection velocities are preferred to optimize fuel atomization and mixing processes. For this reason, injection system suppliers have made efforts to produce injectors with faster dynamic behavior and capable of working at higher injection pressures, which approach square-like injection rate profiles. Johnson et al. [10] studied the injection rate and spray characteristics of a diesel injector in the range of 2000–3000 bar. Wloka et al. [11] combined internal nozzle flow simulations with single-cylinder engine testing, showing that these injection pressure levels combined with a proper nozzle geometry design can lead to soot emissions reduction. Mohan et al. [12] confirmed through multi-cylinder engine testing that the use of ultra-high injection pressures could help to reduce soot emissions, and also engine efficiency and CO/HC emissions. However, such high injection velocities tend to produce steep initial heat release rates, inducing high NO_x emissions and

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cylinder pressure gradients (linked to higher combustion noise) [13]. To mitigate this effect, more and more complex multiple injection strategies have been developed over the years [14]. In this sense, Dhar et al. [15] studied the effect of a pilot injection, coupled with different fuel formulations, to module the shape of the heat release rate and improve the soot-NO_x trade-off. Xu et al. [16] observed that an early pre-injection could help to increase thermal efficiency and reduce NO_x emissions simultaneously on a natural gas fueled engine. Mahr [13] proposed the addition of a late post injection to improve the soot oxidation process. Nevertheless, the use of multiple injection strategies come with the cost of an increased calibration complexity.

Another alternative to produce a similar result would be a direct modulation of the injection rate shape [17]. Mohan et al. [18] studied a boot injection shape through numerical simulations, resulting in reduced emissions compared to a square injection rate shape. He et al. [19] performed simulations on a wider variation of injection rate profiles, being the optimal a so-called "hump" shape, characterized by increased injection rate and velocities in the initial and final stages of the injection event, while reduced values are used in the middle. Benajes et al. [20] assessed experimentally the impact of injection rate shaping by implementing a device to modulate the injection pressure along the engine cycle. Other methods are based on a direct control on the needle position along the injection event [21]. A low needle lift produces a throttling effect on the needle seat, inducing a pressure drop, which results in a reduced injection rate compared to maximum needle lift conditions. Both strategies have shown potential to modulate injection rate, but with the drawback of impaired injection velocity (and consequently spray atomization). Postrioti et al. [22] evaluated the possibility of shaping a main injection event by positioning a close-pilot injection by leveraging the combined effect of the different instantaneous pressure achieve in the sac and control volume and the residual electromagnetic current existing in the solenoid coil from the first injection event. Combustion performance of a similar injection strategy was evaluated by d'Ambrosio and Ferrari [23], with promising results in terms of reduced soot emissions. Nevertheless, such behavior is difficult to be controlled on real engine conditions.

This paper explores a variable-area injector as a way to modulate the injection rate shape minimizing the effect on injection velocity. The variable-area concept is achieved using a pintle nozzle design. Although pintle nozzle designs are not standard in automotive diesel production engines, these designs could be of relevance for alternative architectures such as opposed-piston engines. These architectures typically require combustion systems with side-injection layouts of one or more injectors with narrow plume angle nozzles. For example, Venugopal et al. [24] explored side-injector orientation and control using conventional multi-holed nozzles on a diesel 2-stroke opposed piston to study the impacts on combustion and piston thermal loading. The main difference between the pintle nozzles used in this study and other pintle nozzles studied in the literature [25] is the relative shape of the nozzle and the needle. The pintle nozzles studied in this paper are designed so that the area available for the fluid to pass evolves in a certain way, producing a characteristic injection rate profile. Three different designs are analyzed in the paper by comparing hydraulic behavior and spray characteristics.

The paper is divided in 5 sections. In Section 2, the pintle nozzle concept used for the study is proposed, together with the three different geometries used on it. Section 3 gives some details of the different experimental tools and methodologies employed to analyze the hydraulic performance and spray behavior characteristics. Section 4 summarizes the main findings obtained in terms of their hydraulic behavior and spray characteristics. Finally, the main conclusions of the study are described in Section 5.

2. Description of pintle nozzles

In this section, the pintle nozzle concept proposed along the paper is briefly described and compared to standard diesel nozzle. Additionally, the three pintle nozzle variations used along the study are detailed.

2.1. Concept

A schematic of a standard diesel injection nozzle is seen in Fig. 1a. In these nozzles, three main components can be defined: the needle, the sac and the hole (or holes), which can vary in number and orientation depending on the particular nozzle design. In the case of the figure, a single-hole axi-symmetric hole geometry, as it could be used for side-injection combustion systems, is represented [24]. When the injector is closed, the needle separates the high-pressure region of the nozzle (corresponding to the internal channel where the needle is located) from the low-pressure region, which includes the sac and the discharge hole. When the injector opens and the needle moves up, the mass flow through the nozzle hole depends on the area of this hole, which is constant, and the pressure in upstream section of the flow, which is controlled by the throttling effect achieved in the needle seat region. Thus, controlling the velocity at which the needle opens, it is possible to control as well the fuel injection rate [21].

In the case of a typical pintle nozzle (Fig. 1b) the needle lift affects not only the pressure upstream the hole, linked to the throttling effect in the needle seat, but also the area available for the flow. In the case shown in the previous figure (straight hole and

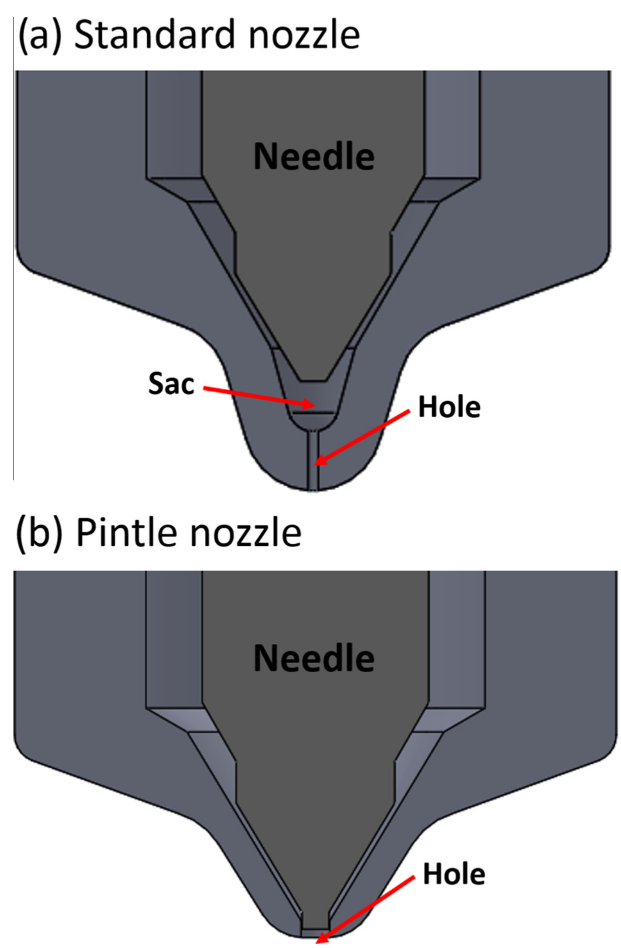

Fig. 1. Comparison of standard and pintle nozzle concepts.