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Experimental and numerical characterization of a direct solenoid actuation injector for Diesel engine applications

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HIGHLIGHTS

- The behavior of a DDI injector was studied by Zeuch method based injection analyzer.
- The spray global evolution was studied by imaging; its sizing and velocity by PDA.
- Eulerian simulations investigated the fuel distribution within the nozzle.
- The simulations reproduce the jets in terms of penetration length and morphology.
- The numerical and experimental comparison of the averaged D10 is acceptable.

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ABSTRACT

In the present paper, a non-conventional Diesel injection system is analyzed by means of a detailed numerical and experimental investigation.

The analyzed system, the Magneti Marelli DDI Diesel direct injection, is based on a direct-actuation solenoid injector. The DDI system operates up to 60.0 MPa injection pressure, with a multi-hole nozzle resulting in a conventional fuel spray plumes distribution inside the combustion chamber, which suites the requirements of small industrial and automotive Diesel applications.

In the present research activity, the hydraulic behavior of the DDI system was analyzed in terms of injected volumes and injection rate time-histories varying the injection pressure from 30.0 MPa to 60.0 MPa with a back pressure of 2.0 MPa. The resulting injection process was also analyzed in terms of spray global shape evolution along with droplet sizing and velocity in a pressurized (1.0 MPa) test vessel in quiescent and room temperature conditions.

In order to investigate and to validate the capability of adopted CFD models to reproduce the spray behavior at such non-conventional injection pressure levels for Diesel applications, an experimental and numerical comparison was performed, in terms of liquid spray morphology, tip penetration and droplet sizing.

A numerical methodology, based on a preliminary Eulerian Steady Simulation of the nozzle, has been developed in order to gain correct flow rates and turbulence data at each of the nozzle holes exit. Then the Lagrangian spray simulations have been carried out by means of a new atomization approach able to take into account the cavitation phenomena and the turbulence effects. A tuning campaign has been performed in order to validate the secondary KH–RT breakup model, and a grid sensitivity analysis has been carried out.

1. Introduction

Over recent years, automotive on-road and off-road systems manufacturers are engaged in significant efforts aimed at reducing polluting emissions and at improving the engines energy efficiency. This trend, mainly due to the introduction of more stringent standards by the industrialized and developing Countries, has significantly increased the engines complexity and therefore their cost; this is due to the hardware sophistication and the complexity of strategies needed to achieve an adequate level of combustion process control.

In this framework, both spark ignited and Diesel direct injection engines require an extremely sophisticated control of the fuel

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Nomenclature

CFD	computational fluid dynamic
C_c	discharge coefficient
CN	cavitation number
C_s	tuning constant
D10	droplet mean diameter
DDI	direct Diesel injection
D_{hole}	diameter of the hole
ET	energizing time
FRF	flow rate factor
K	Bulk modulus
L	length of the hole
Ω	frequency of the fastest growing wave
Ks	tuning constant
n	nozzle holes number
P	pressure
PDA	phase doppler anemometry
P_{rail}	rail pressure
$\dot{Q}$	volumetric flow rate
S	tuning constant
sat	saturation
τ	breakup time
U_{inj}	nozzle flow velocity
V	volume
VOF	volume of fluid
RANS	Reynolds-averaged Navier–Stokes

injection process and fuel mixing within the air, in order to properly mate the desired heat release rate for the overall engine operating conditions [1–5].

In order to achieve an adequate control of the injection and combustion processes, the following key phenomena must be adequately investigated: the accuracy of the injected fuel amount, the delay in the actuation devices and the consequent mass flow rate delivery, the geometric evolution of the fuel spray, its atomization, evaporation and mixture formation.

It is obvious that to control such a large number of phenomena, a combined numerical and experimental characterization is required.

In this frame, the availability of experimental data concerning the key aspects of the phenomenon allows an adequate validation of the numerical tools, so they can be used in the design of the spray-combustion chamber interaction.

For compression ignition engines, the availability of electronic controlled common-rail injection systems allowed to apply complex injection strategies (e.g. multiple injections, rate shaping) in order to obtain significant improvements in terms of emission control (e.g. trade-off between NO_x and particulate matter), specific power, conversion efficiency and acoustic emissions of the engine.

The solenoid operated injector is presently the most significant component of current production common-rail Diesel injection systems. As well known, this kind of actuation does not allow a direct control of the nozzle needle position, which is possible only with a piezoelectric actuation.

Moreover, adopting indirect control system for the needle nozzle causes a considerable increase in injector complexity and consequently in its cost. Therefore implementing electronic controlled common rail injection systems in smaller displacement or in rough off-road engines applications could not be feasible.

In fact, in those contexts, the components cost is often a key factor, restricting the ability to benefit from the advantages due to the electronic control of the injection process in terms of performance and pollutant emission control.

Thus in recent years Magneti Marelli has developed a solenoid operated direct fuel injection system for Diesel engines, called Diesel direct injection – DDI – using a technology derived from gasoline direct injection (GDI) systems.

In this paper, an experimental characterization of a prototype DDI injector hydraulic behavior and spray characteristics was carried out. The mean injected volume and injection rate for rail pressure ranging between 30.0 and 60.0 MPa were measured by a proprietary instrument based on the Zeuch's method. Further, the spray evolution was characterized by imaging allowing the construction of the tip penetration and cone angle curves for all the five jets emerging from the nozzle in a pressurized, ambient temperature test vessel. In the same test vessel, the spray droplets sizing and axial velocity were analyzed by means of a Phase Doppler Anemometer (PDA) along measuring traverses orthogonal to the spray main axis, allowing the construction of detailed droplet size and velocity profiles.

The results of the experimental campaign were then used for the validation of a numerical characterization of the multihole spray. The purpose of this paper is to improve a CFD methodology able to simulate a multi-hole Diesel spray generated at low-medium injection pressure levels. Although the Diesel spray simulation has begun in the 70s, some aspects of the spray dynamics are still unknown. In particular, the mechanisms that lead to the Diesel fuel atomization are still only partially predicted by the most advanced mathematical models: this is mainly due to the difficulty of the experimental investigation in proximity of the injector nozzle. Furthermore, it is becoming more and more clear that the cavitation phenomenon is a significant factor in inducing and enhancing the primary breakup of the spray; historical approaches, which neglect this phenomenon and are based on the prediction of unstable wave motion on the surface of the jet, are still widely used.

A wide number of spray models can be used to simulate the high pressure Diesel injection process. Models based on the Kelvin–Helmholtz wave instabilities such as the Blob approach [6] assume the superficial wave instabilities to be the crucial cause of primary breakup. The model of Huh and Gosman [7,8] introduced the nozzle effects on the primary atomization estimating the turbulence generated by the flow conditions inside the hole. More recently Nishimura and Assanis [9] presented a cavitation and turbulence-induced primary breakup model for Diesel spray that takes into account the cavitation bubble collapse energy.

Despite more accurate models have been developed such as Baumgarten et al. [10], the approaches to turbulence and cavitation require accurate descriptions of the flow conditions through the injection hole. In addition, cavitation models appear far from being predictive since adjustable constants are usually introduced and initial conditions, such as the growing nuclei of the cavitating bubbles, are often unknown.

In this paper the numerical methodology is based on an atomization approach [11] which takes into account cavitation phenomena and turbulent effects induced by the nozzle geometry adopting a simplified approach. Since the primary breakup is expected to begin at the nozzle hole exit, an initial distribution of atomized droplets is predicted by the numerical approach. Due to the low injection pressures adopted in this application, the atomization model originally developed for GDI sprays is tested for the lagrangian simulation of the multihole Diesel spray.