BACKGROUND

The gasoline direct injection (GDI) in spark ignition engines is a promising way to improve simultaneously fuel economy and performances. GDI engines have been introduced over the last years into the European market and operate in two different mixture preparation modes: homogeneous and stratified charge, depending on engine conditions [1-4]. The combustion system geometry needs optimization in order to reduce the fuel consumption and the exhaust emissions [5-7]. To match the power output of multipoint PFI engines, at high loads and speeds, the fuel is injected during the intake stroke under a homogeneous and mostly stoichiometric mixture achieving a higher volumetric efficiency as consequence of cooling due to evaporation of fuel droplets. At low loads the engine works lean; the fuel is injected during the compression stroke and forms a controlled charge stratification, because of the interaction with the air and the piston wall, to concentrate an ignitable charge stratification, because of the interaction with the air injected during the compression stroke and forms a controlled fuel droplets. At low loads the engine works lean; the fuel is efficiency as consequence of cooling due to evaporation of spray is generated by a swirling motion of the fluid inside the swirled injector, has been followed up to last years where a flame propagation [8-15].

In this work a multi-hole GDI injector has been characterized for different operative conditions. The multi-hole approach makes possible a versatile distribution of the fuel in the engine combustion chamber, adequate to the engine setting requirements. Hollow-, full-cone or ellipsoidal footprint structures can be realized orienting the axes of the jets. The spatial and temporal behaviour of the jets, in terms of overall fuel distribution (penetration, cone angle) and local details (droplet size and velocities, break-up and coalescence phenomena), is indicative of the air/fuel mixture preparation for the combustion in the engine. Aim of this paper is to report the experimental work for characterizing the structure of a multi-jet gasoline spray in terms of droplets atomization and dispersion. A multi-hole injector has been used with a hollow-ellipsoid footprint structure of the injected fuel on a plane perpendicular to the spray axis. Commercial gasoline is injected (density 0.76 kg/dm³) with quantities ranging between 10 to 100 mg/str at injection pressures up to 20.0 MPa. High intensity flashes, synchronized with the injection system, have enlightened the emerging fuel from the nozzle developing in an optically accessible vessel in quiescent air at ambient temperature and atmospheric backpressure and the images of the jets have been captured by a CCD camera. The image processing techniques has enabled to extract the main parameters of the jets for characterizing their evolution. Velocity and droplet size measurements have been achieved by a Phase Doppler Anemometry (PDA) system at different locations along and off-axis of one jet.

In the off-axis locations, average axial velocities around 100 m/s are reached for droplets near the nozzle exit while this value decreases to about 80 m/s downstream. Along the spray axis, the velocity increases up to 120 m/s. The droplets diameter, ranging in an interval between 17 and 22 micron, shows an inverse trend assuming higher values for droplets travelling at lower velocities, resulting higher at lower velocities and vice versa highlighting a fragmentation process that is dependent to the droplets speed.

Keywords: fuel atomization, GDI injection, droplet velocity and size, multi-hole sprays

ABSTRACT

In this work a multi-hole GDI injector has been characterized for different operative conditions. The multi-hole approach makes possible a versatile distribution of the fuel in the engine combustion chamber, adequate to the engine setting requirements. Hollow-, full-cone or ellipsoidal footprint structures can be realized orienting the axes of the jets. The spatial and temporal behaviour of the jets, in terms of overall fuel distribution (penetration, cone angle) and local details (droplet size and velocities, break-up and coalescence phenomena), is indicative of the air/fuel mixture preparation for the combustion in the engine. Aim of this paper is to report the experimental work for characterizing the structure of a multi-jet gasoline spray in terms of droplets atomization and dispersion. A multi-hole injector has been used with a hollow-ellipsoid footprint structure of the injected fuel on a plane perpendicular to the spray axis. Commercial gasoline is injected (density 0.76 kg/dm³) with quantities ranging between 10 to 100 mg/str at injection pressures up to 20.0 MPa. High intensity flashes, synchronized with the injection system, have enlightened the emerging fuel from the nozzle developing in an optically accessible vessel in quiescent air at ambient temperature and atmospheric backpressure and the images of the jets have been captured by a CCD camera. The image processing techniques has enabled to extract the main parameters of the jets for characterizing their evolution. Velocity and droplet size measurements have been achieved by a Phase Doppler Anemometry (PDA) system at different locations along and off-axis of one jet.

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The gasoline direct injection (GDI) in spark ignition engines is a promising way to improve simultaneously fuel economy and performances. GDI engines have been introduced over the last years into the European market and operate in two different mixture preparation modes: homogeneous and stratified charge, depending on engine conditions [1-4]. The combustion system geometry needs optimization in order to reduce the fuel consumption and the exhaust emissions [5-7]. To match the power output of multipoint PFI engines, at high loads and speeds, the fuel is injected during the intake stroke under a homogeneous and mostly stoichiometric mixture achieving a higher volumetric efficiency as consequence of cooling due to evaporation of fuel droplets. At low loads the engine works lean; the fuel is injected during the compression stroke and forms a controlled charge stratification, because of the interaction with the air and the piston wall, to concentrate an ignitable mixture in the vicinity of the spark plug for ensuring a fast flame propagation [8-15].

The hollow cone spray philosophy, from a high-pressure swirled injector, has been followed up to last years where a spray is generated by a swirling motion of the fluid inside the nozzle so, under centrifugal force, it spreads out in the form of a conical sheet leaving the orifice. This injection technique was mainly related to injector designs, injection pressures, and fluid properties[16-19]. The new generation of gasoline direct injection engines are based on multi-hole injectors that no longer operate with air-guided charge but instead with a spray-guided combustion similar to diesel process also allowing a much more flexible arrangement of the spray with any combustion concept. The multi-hole approach makes possible a versatile distribution of the fuel in the engine combustion chamber, adequate to the engine setting requirements. Hollow-, full-cone or ellipsoidal footprint structures can be realized orienting the axes of the jets [20,21].

Aim of this paper is to report the experimental work for characterizing the structure of a multi-hole gasoline spray in terms of droplets atomization and dispersion. The injector has a hollow-ellipsoid footprint structure of the injected fuel on a plane perpendicular to the spray axis. The spatial and temporal behaviour of the jets, in terms of overall fuel distribution (penetration, cone angle) and local details (droplet size and velocities, break-up and coalescence phenomena), is indicative of the air/fuel mixture preparation for the combustion in the engine.
EXPERIMENTAL APPARATUS

A peculiar injection system set-up for spraying gasoline through a six hole GDI injector has been adopted. An hydro-pneumatic pump, activated by pressure gas, enabled the injection of the fuel without rotating pump. An input gas pressure ranging from 0.07 MPa to 0.7 MPa has produced a linear output pressure of the fuel from 2.5 to 25 MPa. A reservoir tank pressure of 1 dm3 has been located between the injection pump exit and the electroinjector to absorb the pressure oscillations due to the fuel delivering and the compressed air recharge.

A piezoresistive pressure transducer has been located on the pump-reservoir pipeline connection for the injection pressure collection while a piezoquartz transducer allowed to monitor the pressure oscillations just before the injector connection. A six-holes GDI injector, housed in a pressure holder for connecting the pump to the accumulator, has been used for spraying the fuel. It has been driven by a Programmable Electronic Control Unit (PECU) able to operate in multijet strategy mode with the needle opening time set through the energizing current duration. A sketch of the injection set-up is reported in figure 1. Measurements of the fuel injection rate for the adopted strategies have been carried out by an AVL Meter operating on the Bosch principle [22,23].

For characterizing the overall spray behaviour, the fuel has been injected, at pressures of 10 and 20 MPa, in a high pressure quiescent vessel, optically accessible, at gas backpressures of 0.05 and 0.1 MPa. Images of the sprays, enlightened by powerful flashes, have been collected at different instant from the Start Of Injection (SOI) by a synchronized CCD camera, 1376x1040 pixels, 12 bit resolution, 0.5 µs shutter time. An overview of the experimental scheme for the image acquisition is reported in figure 2. A wet seal spherical holder enabled the tilting of the injector in an angular range of ±15°, with respect to its axis, for the spray orientation in the measurement vessel. This has permitted the alignment of the direction of the jet under examination perpendicularly to the optical axis of the CCD. The captured images have been processed off-line by a processing software for extracting the parameters of the spray.

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Velocity and droplet size measurements have been accomplished at ambient temperature and atmospheric pressure by the Phase Doppler Anemometry (PDA) technique. Simultaneous droplets size and axial component of the velocity have been carried out at locations along a jet axis and a segment at an angle of 4° with respect to the jet axis. The PDA system included an argon-ion laser operating at 514.5 nm, a 310 mm focal length transmitting optics with a beam separation of 65.0 mm and modular collecting optics working in forward scattering mode at an off-axis of 30°. A single aperture of 0.050 mm has been set into the receiver to limit the scattered light to the detectors. The transmitter and collecting optics have been mounted on an x-y-z translation stage that has allowed the positioning of the probe volume within the spray at different locations. A pulse generator has been used to trigger the ECU of the injection system and the PDA processor. The system allowed the reconstruction of size and velocity data along the injection timing with a time resolution of 20 µs.

Experiments have been taken, at ambient temperature and atmospheric pressure, injecting the fuel within a vessel under quiescent conditions with the bottom of the vessel connected to an exhaust blower to extract, under a low velocity co-flow air, fuel droplets. Experiments have been performed running the injection system at the frequency of 1 Hz, acquiring data over 180 injection cycles in order to build a data sample for reliable statistical analysis. The cycle-resolved data have been analyzed off-line by applying the ensemble averaging technique in order to provide the axial mean velocity and the average mean diameter (D10) [24].
with the others. Test points have been located on a plane across the vertical jet-axis, as shown in figure 3 that depicts the layout of the measurement grid at different distances from the nozzle, namely 10 and 20 mm both along the spray axis and at the off-axis distances of 0.7 and 1.4 mm.

EXPERIMENTAL TESTS AND PROCEDURES

A six-holes GDI injector has been tested injecting gasoline ($\rho=740$ kg/m$^3$) in a single pulse strategy. The injection pressures have been 10 and 20 MPa with the pulse durations calibrated for delivering 20 and 50 mg/str for both the injection pressures.

![Fig. 4 - Energizing solenoid current, fuel injection rate and pressure oscillations in the pipeline](image)

Figure 4 reports a typical energizing solenoid current (bottom), the relative fuel injection rate (middle) and the pressure oscillations in the fuel pipeline (top). The sketched condition is relative to a pulse duration of 2.6 ms in which a gasoline amount of 50.88 mg at the injection pressure of 20 MPa is delivered. A delay of 0.4 ms has been registered between the start of injector coil energizing and the exiting of the fuel from the nozzle. The fuel injection rate signal shows an initial overshoot peak at the opening condition while stabilizes after 0.45 ms up to the end of the injection. The choice of the injected fuel quantity is controlled by the pulse duration once set the other parameters. The pressure oscillations at the top of the figure, generated at the nozzle opening, are collected by a piezoquartz transducer. The peak amplitudes start from an initial value of 0.9 MPa and reduce at longer time. Their intensities and time locations could influence the fuel injection rates for next pulses in multiple injection strategies but are negligible for injections in the next engine cycle.

The images of the jets, for the overall spray parameters, have been collected both in parallel and orthogonal conditions with respect to the spray propagation. In the measurement vessel the injector has been located with the propagation axis of the jet #4 orientated in normal (set-up A) and parallel (set-up B) way with respect to the CCD optical axis to avoid angular corrections. Figure 5 reports, at atmospheric backpressure of the gas, the visualization of the spray in both the set-up at 0.2 ms from the SOI and 20 MPa injection pressure. A set of 5 images has been collected for each injection condition for a statistical analysis of the cycle-to-cycle dispersion.

The tip penetration and the spray-cone angle have been measured to characterize the performance of the spray at the fixed conditions. The capability of the experimental apparatus to orientate the injector for confining the jet #4 has enabled to oversee its evolution for long time, greater than 2.0 ms. The main hypothesis is that all the jets behave in a similar way.

![Fig. 5 – Spray visualization at 200 ms from the SOI for A and B acquisition set-up](image)

This condition could not be true at later time (> 1.0 ms) when the sprays swelling produces an interaction with no negligible influences both on the droplets penetration and sizing.

The processing analysis of the images has been carried out in different steps: image acquisition and background subtraction, filtering, fuel spray edges determination, tip penetration and cone angle measurements. The image has been stored and processed off-line by the Image Pro-Plus software. Background subtraction and median filter procedures have been adopted during the image acquisition to remove impulse noise and stray light so maintaining sharp the spray edge. These have been determined selecting an intensity threshold level for separating the fuel region from the background ambient gas. Tip penetrations and cone angles have been determined from the contours. Figure 6 illustrates this procedures trough diagrams while further details are reported in [25].

![Fig. 6 – Procedures for digital processing of the images for spray parameters acquisition](image)
RESULTS AND DISCUSSION

Image sequences of the spray evolution, for the A and B set-up, are reported in figure 7. In this figure the two extreme conditions of the tests are reported: 20 MPa injection pressure, 50 mg/str of delivered fuel and atmospheric backpressure of the gas in the vessel, at the top, while 10 MPa injection pressure, 20 mg/str injected fuel and 0.05 MPa gas pressure in the vessel at the bottom. The frontal view of the sprays highlights the jet plumes and their independent evolution up to about 200 μs from the SOI for the 20 MPa condition (top). The jet propagations are clear and indicate the fuel distribution inside the vessel. This regularity appears destroyed for the 500 and 700 μs images where the interference between the single jets appears evident and the single jet evolution can not be longer followed. Here the fuel has to be considered as a single, large and composite spray. The lateral spray evolution view (set-up B) allows to distinguish the origin of the single jets close to the nozzle exit. Four single, well confined arrows appear in the CCD view plane while the last two are covered because in the back side.

The orientation of the injector, with respect to the camera, enables a complete view of the jet #4 both for the tip and the bottom side evolution while, in the upper side, the droplets interfere with neighbour jets and are confused with clusters coming from the other jets. The lateral view of the spray points out a complex structure of the evolving jets, too. In fact, mainly at later time, bunches or fuel pockets appear in the jet images highlighted by higher intensities of the scattered light. This aspect is indicative of a non homogeneous distribution of the fuel inside the jet and is...
peculiar of the fluidodynamic conditions in the injection process. In the bottom part of figure 7, the spray evolution is quite similar but experiences the worst injection conditions (lowest pressure, less fuel and vessel gas depression). In fact, the interference between the jets starts early (100-150 μs) and the jets can not longer be considered isolated. The sequences of the images for the other setting (injected quantity, fuel pressure and gas backpressure) are conditions intermediate between that described in figure 7.

The effects of the injection pressure on the tip penetration and spray-cone angle, for the jet #4 at 50 mg/str of injected fuel and atmospheric backpressure conditions, are reported in figure 8. Both the profiles show a similar trend with a quite linear behaviour of the penetrations up to 500 μs.

At later time, a bend in the shape in the logarithmic sense is observed. Highest is the injection pressure longest penetration produces. In fact, at 500 μs from the SOI, penetration values of 62.38 mm are reached for 20 MPa injection pressure curve respect to 54.94 mm for the 10 MPa pressure while, at 2000 μs, these values are 97.81 and 87.77 mm, respectively. The spray-cone angle curves show slightly lower asymptotic values for higher injection pressure condition. These values are 11.9° for 20.0 MPa and 12.4° for 10.0 MPa, respectively.

Figure 9 reports the tip penetrations and the spray-cone angles parameterized to the pressure in the vessel for 10.0 MPa injection pressure and 20 mg/str injected quantity for the jet #4. The analyzed backpressures have been 0.10 and 0.05 MPa, respectively. From the figure, negligible effects on the penetration can be noted, in the limits of the experimental errors, while effects on the spray-cone angle are present. In fact, asymptotic values are registered of 12.8° and 11.5° for 0.10 and 0.05 MPa gas pressure. The brake effect of the gas on the fuel dispersion is less in sub-atmospheric than atmospheric backpressure with influences on the jet swelling. Finally, no effects are observed on the tip penetration and spray-cone angle due to the amount of injected fuel confirming that the injection pulse duration is the only controlling parameter. Longer is the injector energizing higher is the injected fuel quantity without effects on the fluidynamic of the spray evolution.

Time-resolved mean diameter (D10) and axial velocity of the droplets in the spray have been estimated by the PDA technique using the ensemble averaging procedure over 180 injection cycles. The droplets distribution represents a great concern to provide reliable spray parameters, therefore some thousands of single droplets have been evaluated, for each data set, in order to estimate the mean diameter.

Measurements have been made on of the jet #4 that is non-interfering with the others both along the spray axis and at off-axis distances as already pointed out in the experimental set up paragraph. In figure 10 the profiles of the axial component of the droplets velocity and the droplets diameter along the spray axis, are reported. The first appearance of data highlights a delay time with respect to the axes origin corresponding to the injection characteristic delay time of the system to deliver primary fuel droplets plus the flight time of fuel droplets to reach the sampling volume. The axial velocity
profiles, plotted on the right side of figure 10, show an early increasing trend, representative of the transient needle opening stage, and a rough constant and regular fashion during the steady state part of the temporal spray development. Finally, the droplets axial velocity depicts a decreasing trend up to negligible values at the end of the injection. The location closer to the nozzle shows the highest velocity values, about 120 m/s, compared to the 100 m/s obtained at the location at 20 mm from the nozzle that also exhibits a slight decreasing trend during the steady state injection may be due to flow momentum transferred by adjacent jets.

Looking at the droplets size profile, figure 10 right plot, it can be observed an opposite trend if compared to the velocity profiles, during the transient needle opening period with lower decreasing values for the location closer to the nozzle and almost overlapping values during the later injection stage.

The investigation has been also conducted at off-axis locations of the jet #4 whose results are shown in figure 11. The droplets axial velocity has a decreasing trend during the transient stage of injection, while it highlights an almost constant profile during the steady state period. The spot closer to the nozzle (x=0.7 mm; y=10 mm) exhibits higher axial velocities (about 100 m/s) compared to the farther one. The droplets size shows an opposite trend, with bigger droplets (from 20 to 22µm) located at the periphery of the measurement point farther from the nozzle, highlighting of a fragmentation process that is dependent to the droplets speed. The droplets diameter is not much affected by the near nozzle location except a slight decrease at the spray periphery (down to 17µm). More fluctuating profiles may be observed moving toward the spray periphery because of the interaction with the surrounding air that produces wide fluctuations.

Velocity and droplet size measurements have been performed at ambient temperature and atmospheric pressure by the Phase Doppler Anemometry (PDA) technique for locations along and off-axis within a single jet.

The main results can be summarized as:
- the plumes of the single jets develop independent each other for different time from the SOI depending on the injection conditions. At 20 MPa the jets start to interfere later than 200 µs;
- fuel pockets appear in the jet images indicating of a non homogeneous distribution of the fuel inside the spray;
- the injection pressure strongly influences the penetration of the tip while the gas pressure in the vessel and total amount of delivered fuel produce negligible effects;
- the gas backpressure influences significantly the spray-cone angle while slight effects come from the injection pressure and no variations are due to the injected fuel amount;
- the droplets axial velocity, estimated during the steady state period of injection, gives values up to 120 m/s in the nozzle near field with a rapid decrease downstream and an almost flat profile;
- the droplets size in the near nozzle region does not change significantly, providing values about 20 µm, with a slight decreasing trend, for off-axis locations, during the injection evolution.

CONCLUSION

A multi-hole GDI injector has been characterized at different operative conditions in terms of overall fuel distribution and droplet size and velocities inside the spray. Tests of a single pulse strategy at the injection pressures of 20 and 10 MPa, delivering an amount of fuel of 50 and 20 mg/str, respectively, with 0.1 and 0.05 MPa as gas (N2) backpressure, have been performed. The morphology of the spray, jet development, as well the velocity and size of droplets on one single jet have been investigated.

The global evolution of the spray has been investigated by the imaging technique applying the digital processing of images, acquired by a synchronized CCD camera in two orthogonal set-up.

In summary, it can be observed that in the early transient stage of injection there is a increasing trend for the axial velocity owned by droplets that is opposite to the trend held by the droplets size profile; during the steady state period the velocity has an almost flat profile with axial velocities decreasing with the distance from the nozzle and droplets size that do not change significantly. This suggests that the physics of the atomization near the nozzle region is due to the aerodynamic instability that causes the liquid film to break-up and it can be assumed that, for the investigated locations, the main parameters controlling the atomization are drag and collision.
REFERENCES


