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Spatial Analysis of Fuel Density from Automotive Transient Sprays by Polycapillary X-Ray Imaging

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Abstract

Attempts to study fuel density distributions inside transient high-density fuel sprays by X-ray based techniques have been carried out in several laboratories around the world. Synchrotron radiation as X-ray sources are mainly adopted due to their high intensity and pulsed nature. On contrary, this sources have the intrinsic limitations of high costs, beamlines with dedicated instrumentation, poor duty cycles.

In this paper laboratory desk-top X-ray techniques based on polycapillary optics has been used for investigating the structure of a gasoline pulsed spray for automotive applications flowing from a GDI injector. Polycapillary optical elements enable shaping divergent X-ray beams as well as getting high contrast image of the samples due to the suppression of radiation multiple scattering. A Cu Kα X-ray source in combination with a polycapillary halflens (semilens) has been used while the extinct radiation by the sample has been collected on a CCD detector. Two injectors, a single-hole hollow-cone and a six-hole, worked at 8.0 MPa injection pressure and sprayed gasoline at atmospheric backpressure in a Plexiglas chamber. This has been vented to prevent fuel fog accumulation and sheltered by Kapton foils 25 μm thick on the optical beam line to avoid droplet/vapor leakage. The injector-pressure pump coupling has been realized through a complex fuel reservoir composed of two parts: fixed and rotating. The last one permitted the rotation of the injector body around its axis by mean of a stepping motor so enabling to irradiate the spray under different angles. Off-line tomography reconstruction has been made with the images with an acquired angular steps of $\Delta\theta = 1°$. Measurements have been carried out close to the nozzle tip and the computed tomography has permitted average reconstruction of the fuel downstream the nozzle tip.

Introduction

The future development of internal combustion (i.c.) engines faces the improvements of the combustion efficiency, mainly the fuel consumption and pollutant reduction. In this process, the feeding of the fuel covers a key role being devoted to an effective air/fuel mixing for next the combustion. High pressure sprays have been experimented for a better rupture of the liquid bulks in order to enhance atomization and vaporization. Experimental and modeling approaches are pursued for design and strategy definitions. Quantitative data on the jet behavior are necessary, especially in the regions close to the nozzle tip, where a great interest for understanding break-up processes and formation of the next structures start [1, 2]. Mainly, investigations are carried out in hostile ambient by laser-based non-interfering tools and using radiation in the visible-UV range to measure spatial fuel density, droplet dimension and thermodynamic behavior [3, 4]. Unfortunately, these techniques show strong limitations in high fuel-dense or strongly atomized regions where absorption effects and multiple scattering of the incident light vanish the approach restricting it to low-dense surrounding areas of the spray.

Recently, non optical-based techniques have been approached for investigating high-dense regions of finely atomized droplets. X-radiation penetrates the dense part of fuel spray because of its weak interaction with the hydrocarbon chain and useful information is provided from the emerging radiation [5]. Time-resolved X-ray radiography and tomography have been used to elucidate three-dimensional structures both for gasoline and diesel spray in close-nozzle high-dense optically-impenetrable regions allowing quantitative data on fuel densities, jet structure and morphology, induced shock waves, droplet ruptures [5-7]. Typically, all these works make use of pulsed high-brilliant sources, like synchrotron radiation. They overcome the initial limits of X-ray tube sources [8-10], continuous in time and energy dispersed in wavelengths, providing monochromatic beams, pulsed time-structure and high time resolution. For example, the Advanced Photon Source (APS) in Argonne produces brilliant wide band X-ray radiation (~ 10^{17} photons s^{-1}) that, with a monochromaticity of the order of 10^{-4}, makes available about 10^{12} photons s^{-1} on a 0.6x0.3 mm^2 beam spot [11]. These sources have the advantage of a periodicity nature so helping in the discrimination of the pulsed phenomenon, like the sprays are. On the contrary, the high quality and performing synchrotron radiation facilities have restricted access to experimental campaigns because of a few and highly expensive plants worldwide-dislocated, no

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friendly-available, busy beamlines with poor duty cycles and dedicated instrumentation managed by specialists not always available in the research groups. These are part of the motivations inducing people towards X-ray sources suitable for table-top experiments. Usually, they make use of electronic devices for realizing resolution in time, customized optics for brilliance gains while additives with high molecular cross-sections are put into the fluid to enhance the absorptions from the hydrocarbon chains [12-15].

This work aims to report the first results of a table-top experiment using a microfocus X-ray source for radiography and tomography of gasoline sprays for automotive applications coming from a Gasoline Direct Injection (GDI) device and operating at engine-like pressure. A Cu Kα X-ray source at 8.048 keV in combination with a polycapillary halflens has been used to focus the radiation on the desired spray region while a CCD detector for X-radiation has collected the emerging signal. Polycapillary semilenses are the systems for shaping the divergent X-ray beams from the sources into parallel ones (enabling additionally to suppress multiple scattering in optimized geometry) that allows the acquisition of images with high contrast [16, 17], with an incremental radiation intensity gain of 1-2 orders of magnitude. The injector has been inserted in a rotating device actuated by an electronically controlled stepping motor with the 0.1° angular resolution. The acquisition has been carried out on 180° angular trip at the injection pressure of 8.0 MPa in the zone immediately downstream the nozzle. Digital processing of images has permitted sinograms reconstructions of the jets by slices allowing to access to the spray 360°- degree and inside the volume. Two different kinds of injectors have been used: a hollow-cone type producing a cone-shaped structure with highest density on the cone external surface and a six-hole multijet generating a complex structure of the global spray with squirts developing along defined directions.

Experimental Apparatus and Procedures

The X-Ray radiography technique has been applied to detect the characteristics of dense cloud of droplets, like that coming from fuel injectors for internal combustion (i.c.) engine, to overcome the high absorption and multiple scattering occurring when visible light-based techniques are used. In particular, tomography has been utilized in a setup configuration that has seen the sample rotating on its main axis with angular steps of 1° with respect to the X-Ray source/CCD detector line-of-sight. A GDI injection apparatus for gasoline engine has been used fitting two different injectors and producing sprays of diverse geometries: a hollow-cone one with the cone axis coincident with that of the injector and a multihole one (six holes) with the jet axis suitably oriented.

X-Ray Tomography Concept

Computed and micro-computed tomography (CT and microCT) are nondestructive techniques, which provide high resolution images of the internal structures of the investigated objects. X-ray imaging slice data is generated using an X-ray source rotating around the object; it is possible to collect a set of projection images by positioning a detector (usually a CCD) on the opposite side of the circle from the X-ray source. It is possible to collect a set of projections by means elaboration applied to the obtained. Such 3D reconstructions are used to study sample’s inner structures and details, to investigate its fine morphological variation and to perform advanced morphometric analysis of a sample.

However, it is difficult to get high contrast images, high signal/noise ratio and short exposure times due to the high diffusivity of the conventional sources. In order to overcome the problems, it is necessary to realize a microfocus X-ray source combined with an optical device characterized by low residual divergence of transmitted radiation.

Nowadays, the X-ray industry proposes various well-known solutions for X-ray microsources, while for conventional X-ray sources only polycapillary condensers work effectively. Polycapillary structures meet growing interest due to their potential applications in X-ray optics [17, 18]. As known, a capillary is characterized by a hollow inner cavity, which could act as a channel for selective radiation penetration. This produces strong radiation redistribution behind capillary systems, revealing essential structural behavior due to the spatial system geometry [12].

Research concerning X-ray propagation in capillary structures shows that diminishing the capillary internal radius, down to micron and submicron, results in the ability of handling the radiations of higher quantum energies as well as of focusing them in much smaller spots. For instance, while the first polycapillary systems have been able to concentrate X-rays in spots sizing hundreds or tens microns, the last generation lenses (the 5th generation of polycapillary optics has been recently announced [19]) enable to shape X-ray beams with micron resolution and mrad divergence. The latter becomes very attractive for different applications based on both focusing and imaging efficiencies of the used optics.

Injection System

The injection apparatus consists of a hydro-pneumatic pump activated by a pressured gas, a hollow-cone and a multihole injector for gasoline direct injection in spark ignition engines and a programmable electronic control unit for pulses managing and control. The pump produces fuel pressures from 2.5 to 25 MPa for gas pressures ranging between 0.07 to 0.7 MPa. Commercial gasoline has been used (ρ=740 kg/m^3) with a Cerium additive (6% in volume) to enhance the low absorption cross-section of the fuel at the considered X-Ray energy [20]. The fuel has been injected at 8.0 MPa pressure in an optically accessible Plexiglas vessel at atmospheric backpressure and ambient temperature.

The doped oil has been delivered by solenoid actuated GDI injectors (13.7 g/s @ 10 MPa flow rate). Two devices, with different number and geometry of holes, have been used to test the tomography technique and compare the results in different image contests. A hollow-cone injector with an axially-disposed exit, 0.5 mm diameter, distributed the fuel over a cone surface caused by inner tangential ducts imprinting an angular momentum to the fuel bulk; a multihole one with six exits, 0.193 mm in diameter each, which axis orientation configured the shape of the evolving spray.

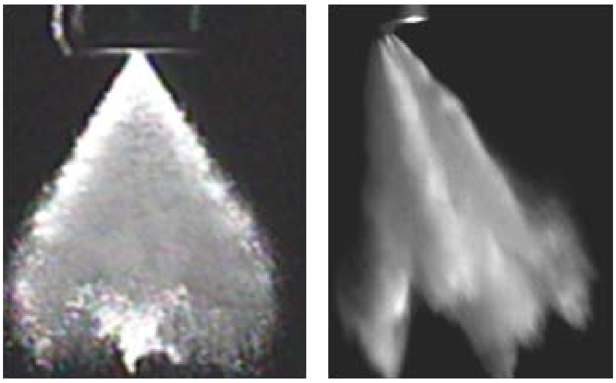

Figure 1 Hollow cone (left) and multijet (right) images of GDI sprays at 100 MPa injection pressure and 300 μs after SOI

Figure 1 shows the sprays produced by the two configurations obtained by light scattering technique in visible range. They delivered pure gasoline at 10 MPa injection pressure, 0.1 MPa backpressure and ambient temperature; the images refer to 300 μs from the start of injection.

A programmable electronic control unit (PECU) starts the injection event and triggers the acquisition of the CCD by TTL-based signals. To enhance the signal-to-noise ratio, background has been cut off the injection event. The acquisition is in a time-window synchronized with the injection event. Its duration is equivalent so resulting in any time resolution of the tomography tests. A time resolution can be obtained reducing the acquisition time-window of the CCD and shifting it respect to the start of injection. A sketch of the experimental apparatus is reported in figure 2 while further details can be found in [21].

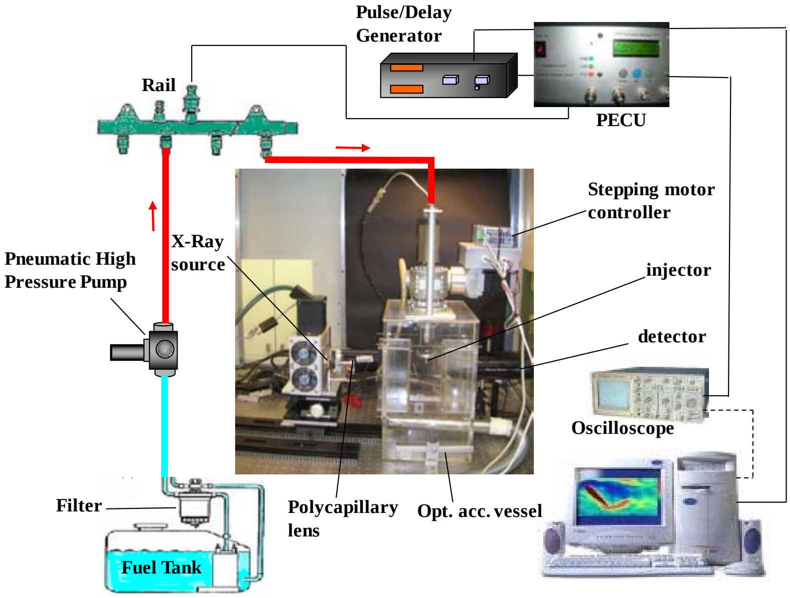

Figure 2 Sketch of the experimental set-up including the injection apparatus and the X-ray source-detector system

To realize the setup for tomography applications a homemade rotating device for the injector has been designed and successfully tested at high pressure. The system allows a controlled trip, 360 degree rotation - 0.1 degree precision step, of the injector body working at pressures up to 20 MPa. The challenge has been to realize the coupling between the fixed and the rotating parts at high pressure, preventing fuel loss. The device has been designed as an assembly of several components in order to quickly change parts without compromise the system set-up.

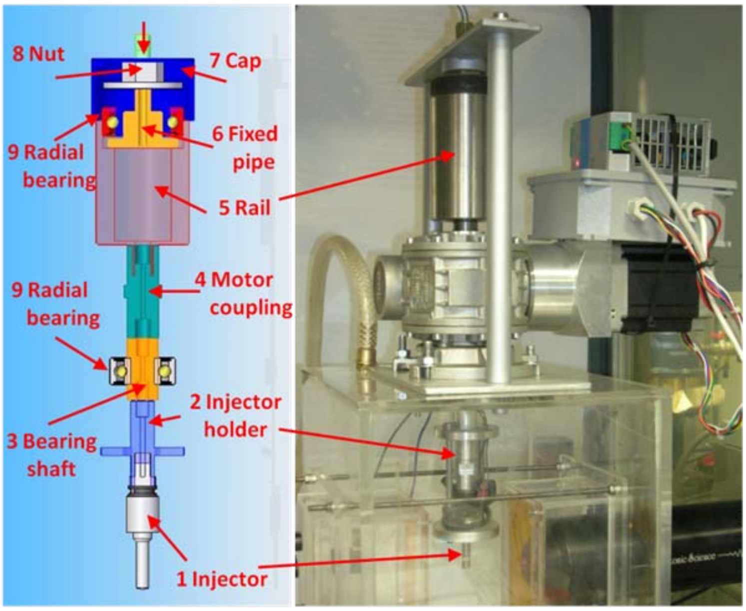

Figure 3 Fuel-tight high-pressure rotating system: schematic sketch on the left and photo on the right

Figure 3 depicts a sketch of this system, on the left, while a photo of its allocation in the experimental setup is reported on the right. A hollow shaft links the GDI injector (part 1 in the figure) to a fuel accumulation tank (5-Rail). The shaft is composed of three parts: an injector holder (part 2), a chamber coupling by means a radial bearing (part 3) shaped to be housed on the speed reducer shaft (part 4) coupled with a stepper motor. All parts are connected by male-female threads and o-ring gaskets. The reservoir (part 5) works as high pressure rail accumulator to avoid pressure fluctuations during the injection phase.

The relative motion between the rotating fuel accumulator and the fixed part of the fuel pipe has been achieved through the radial bearing shown in the figure as part 9. In fact, the outer ring of bearing has been mounted to rotate together to the inner part of the rail, while the inner ring of the bearing is fixed and coupled with the fixed pipe (part 6). The high pressure fuel in the tank forces the pipe against the inner part of the bearing. An o-ring gasket ensures the sealing of the system at high pressure. A cap (part 7) is screwed on the rotating rail to fix it to the outer ring, while the nut (part 8) together with a washer connects mechanically the pipe 6 with the inner bearing wheel. The rotation of the system is induced by a high-torque stepper motor controlled in direction, total angle and angular step by an ECU.

The injection and image acquisitions are carried out in a transparent chamber at atmospheric backpressure. The vessel is in Plexiglas material and is provided with two large windows on the X-Ray source/CCD detector line of sight to permit the radiation passing through. Two thin Kapton sheets (25 μm) keep away from gasoline droplets and vapor exiting from the vessel while an exhaust blower vents the system preventing the fuel fog to fill the chamber and accumulate on the Kapton windows. The blower has operated at low velocity avoiding interference with the spray plume.

Tests and Procedure

The experimental activity has consisted in tomography measurements using X-rays from a Cu Kα source (50 kV, 1 mA, spot 45x45 μm^2) on a periodic, transient and unshaped sample like a real spray. The contours, local densities and morphological structure (droplet size, ligaments, and vapor) of a fuel spray for i.c. engine are quite different shot-by-shot requiring average-based techniques for collecting useful information. The laser-based investigation technique have shown limits in penetrating the dense regions of droplet clouds, like sprays, while the X-radiography, characterized by high penetration efficiency, can give information on the droplet clouds structure and behavior. On other hand, world-wide used CFD codes, for simulating fuel bulk actions when injected in combustion chamber, request basic information on droplet size distributions and behavior, parameterized at the engine conditions, for calibration as well as for comparing the results.

The experiments have been performed in simplified conditions to isolate basic phenomena and investigate the injected droplet history at engine-like conditions. In the experimental apparatus paragraph the X-ray source/CCD detector positioning and alignment has been described. They are situated faced to the Kapton windows in the injection chamber and aligned close-up the injector tip. The results reported in this paper are referred to a position of the injector axis perpendicular to the source/detector line-of-sight. The investigated area has been close to the exit of the nozzle with a size of about 16 mm^2. The injection apparatus has been set at 8.0 MPa injection pressure with duration of 3.0 ms and a repetition rate of 4 Hz. The set-up conditions are summarized in Table I.

Table I Set-up and experimental conditions

Injector 1: hollow-cone	Φ: 0.5 mm
Injector 2: six-holes	Φ: 0.193 mm
Injection pressure [MPa]	8.0
Ambient pressure [MPa]	0.1
Ambient temperature [K]	293
Inj. energizing time [ms]	3.0
Detector acquisition time [ms]	4.0
Rotation step resolution [°]	1

X-Ray source	Cu Kα; 50 kV; 1mA
X-Ray spot	45x45 μm^2
Transmitting optics	Polycapillary lens
Investigated area	16 mm^2
Fuel	Gasoline
Additive [%]	Cerium [6]
Detector	CCD - FDI 1:1.61
Detector resolution [μm^2]	3.5x3.5

The fuel with Cerium additive (6% in volume), has been supplied to the injector in the experimental cabinet through a high pressure pipeline while the vapor produced in the test chamber has been extracted and compensated with fresh air to avoid low pressure conditions. The rotating apparatus has been driven by a step motor-speed reducer system performing a complete round, step 1°. The injection tip precession, due to misalignments, has been evaluated comparing four images of the nozzle collected at 90° each other. The tip displacement varied in a range less than 1 mm; the injector body (7 mm) has been used as calibration gauge. Each measure point has been averaged on 48 spray events (images) to improve the signal-to-noise ratio.

The experimental setup with a cabinet and an optical table has been designed and developed specially for R&D of X-ray optical systems at the Laboratori Nazionali di Frascati (LNF) [22]. The radiation source has been a (Oxford Apogee 5000) 50 W Cu X-ray tube with a source spot size of about 50 μm. A polycapillary half-lens [14, 22], has been used to obtain a quasi-parallel beam. Its length is about 60 mm, the inlet and outlet dimensions are 3 and 4 mm, while each single channel has an average diameter of about 5 μm. A residual divergence of about 1.4 mrad and a total transmission of about 60% for Cu X-ray characteristic lines have been measured. The possibility to get a very little blurring effect, due to rather small radiation divergence behind the optics, avoids diffraction effects on the sample edges, i.e., far from a wave zone, as well as multiple scattering radiation in matter.

The detector is a Photonic Science CCD camera (FDI 1:1.61) with a sensitive area of (14x10) mm^2 and (3.5x3.5)μm^2 pixel size, with 12 bit image digitalization. The acquisition CCD detector has been synchronized via external trigger with the injection event. Its time acquisition duration is defined by the enabling TTL pulse duration. At this stage the temporal resolution has not been pursued. A time resolution of the system is achievable reducing the duration of the enabling pulse and synchronizing it at different time from the start of the injection. On the contrary, the signals reduce in intensity and highest repetition rates are necessary with the unavoidable problems of fuel deposits and fog. The best compromise between the detector intensity and the number of acquisitions should be found. Likewise for the space resolution, slits or spatial windows can be adopted to reduce the focused area of the spray. A grid on the spray pattern must be defined with the consequence of a huge increase of the investigated locations [23] and the stray radiation from the edge of the slits/pin-holes.

To reconstruct projection imaging into axial tomography and rendering, Octopus by inCT [25], and Amira by Visualize Imaging [26] software have been used. The software Octopus is a package for tomography data reconstruction. Octopus combines high performance reconstruction routines for parallel, fan, cone and helical cone beam data with advanced artifact reduction methods. As a second step, from the reconstructed slice images, the Amira Package delivers a wide range of visualization techniques and interactive manipulation capabilities.

Results

Figure 4 reports the image of the X-ray extinction from a six-hole GDI spray at 8.0 MPa injection pressure and 3.0 ms in duration. The X-radiography of the spray has been carried out with an injector rotation of 180°, step 1° with the images stored and processed off-line. The picture is a sum of 48 images, 12 bit resolution with the detector acquisition as long as the spray duration. At the top-left side, the raw image is shown as integrated on the CCD. The top part shows the tip of the injector; it is recognizable by the black region while the circular-shaped brightness corresponds to the investigated area. Finally, traces of three jets are shown with the remaining jets hidden in the back. At the bottom of Figure 4, left side, the trace of the intensities along an arbitrary profile through the jets is depicted. The huge noise on the outline could destroy the sinogram constructions. To minimize the stray signals (caused from the deposition of the droplet on the Kapton sheets and residual fog) and the injector precession mode during the rotation, acquisition of background images have been carried out per each measurement point. Background subtraction, intensity stretching, low-pass filtering and contrast enhancing have been applied to process the images. An example of the result is reported on the right side of Figure 4. It depicts a clearer area, confines the spray and defines the contours of the jets. This procedure reduces strongly the noise as shown on the profile intensity line reported at bottom on the right. The final result could be further improved increasing the number of acquired images per angular step (hundred or more) or increasing the angular resolution (to 0.5 or 0.1 °). Analogues handling has been reserved for the hollow cone injector; the results are reported in Figure 5. Here the reading of the figures is quite complicated because the spray develops in two phases.

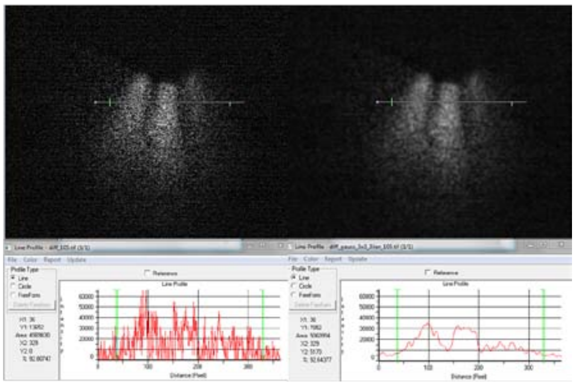

Figure 4 X-ray tomography picture the of the six-hole GDI spray (left) undergoing image processing (right) and relative intensities along a line profile at 8.0 MPa injection pressure

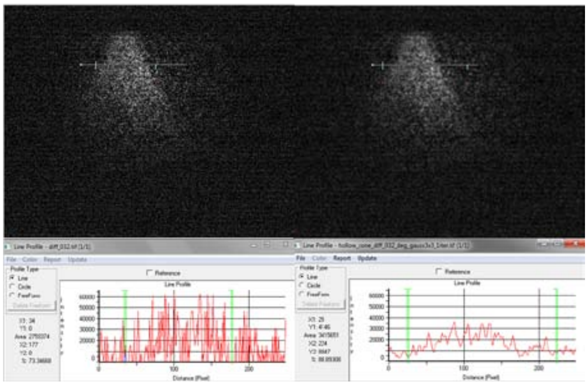

Figure 5 X-ray tomography picture the of the hollow cone GDI spray (left) undergoing image processing (right) and relative intensities along a line profile at 8.0 MPa injection pressure

At early time, the hollow-cone structure distributes the fuel on the cone surface respect to a relatively empty core (t ~ 300 – 400 μs). At later time, the hollow-cone structure destroys itself, because of the interaction of the fuel with the surrounding gas, generating recirculation curls of droplets inside and outside the cone [26]. The actual detection system does not resolve in time so a quasi-uniform structure of the pixel intensities appears along the spray due to the overlapping of all the spray phases. Anyway, the left side of the Figure 5 shows at the bottom tremulous signs of the spray overlapped with a high noise. The adopted procedure of image processing reduces the spikes resulting in a better definition and evidence of the fuel, right part of the figure.

Reconstruction of the Spray Structures

Ideal projections for tomography reconstructions are images free of noise. In practice this is never the case due to the statistical nature of the measurements. Low noise is present in measures of static and unanimated objects: sprays are not in this set. Sprays are periodic events of evolving objects (droplets, ligaments, bulks) that changes continuously shape and thermodynamic conditions during their life-time (typically order of milliseconds).

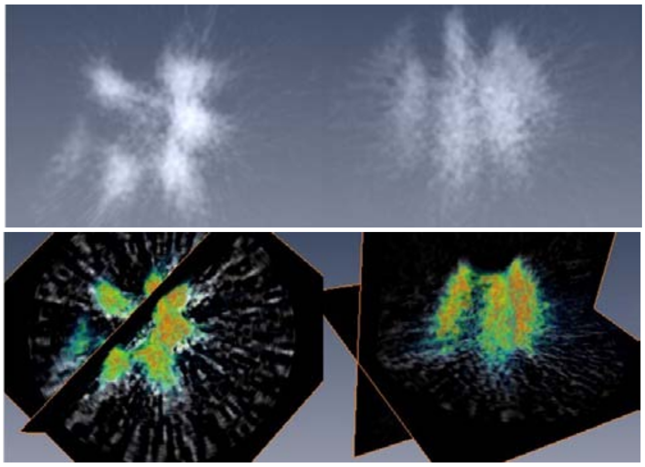

Figure 6 Tomography pictures of the six hole GDI spray (top) and their pseudocolors footprint intensities along intersection planes (bottom)

Repetitions and ensemble averages do not warranty identical conditions at the same spatial and temporal coordinates. A good practice could be to collect a huge number of images per each projection, high angular resolution in conditions of low fog, avoiding fuel deposits on the Kapton sheet (optical axis). The reconstruction of the spray structures has passed through the re-organization of the projections in sinogram. Sinogram is the 2-D array of data containing the projections. In the case of parallel beam geometry, like we consider it is in our set-up because of polycapillary optics, every sinogram produces one reconstructed slice. In the case of divergent/convergent beam more sinograms are needed per slice.

Figure 6 reproduces the reconstruction of the six-jet spray structure as obtained from the sinograms. The field of view of the object is limited to the part immediately downstream the nozzle tip, typically few millimeters. In the top part of Figure 6, two views of the jets are reported: on the left a sight from the top (injector body) is seen while, on the right, a lateral view. The image on the left shows clearly the footprint of the spray, viewing positions and propagating directions of the six jets. No interferences of squirts occur at these locations; the fuel, delivered from the different holes, propagates in an independent way and the profiles appear distinct. The last spurt on the left appears feebler due probably to the acquisition limited on 180° and not 360°. The top-right part shows a side view of the jets, along their elongations, surrounded with spread droplets. These are imputable to noise in the sinogram reconstructions or stray parcels resident in the measurement chamber. The bottom part of figure 6 reports the same images in pseudocolors; a couple of orthogonal planes, passing through the spray and translating respect each other, gives evidence of the resulting footprints along the axial and radial directions in their intersections with the fuel jets. No determinations at this stage have been carried out of the local densities both of the fuel and droplet diameter or parcel structures. The system must be calibrated with known parameters while further improvements need in the experimental set-up, mainly concerning the time-resolved acquisitions. A 3D-simulation activity on X-ray refraction is running with this purpose: the provisional code has been developed to fulfill these requirements [27].

Figure 7 Tomography picture of the hollow-cone spray

Figure 7 reports the tomography reconstruction of the hollow-cone spray. Considerations concerning the quality of the images are analogues to that for the six-jet configuration. The X-ray tomography captures the structure of the jet in its elongation and cone-angle while the lack of resolution in time does not give reason of the inner composition. A light increase of the parcel density can be captured on the boundary of the cone-shape and at the bottom. This is due to the overlapping of the fuel occurred along the entire duration of the injection while the hollow-cone structure symptom appears in top-center part as lower density.

X-Ray Tomography vs. Light Imaging Comparison

Although the setup apparatus for X-ray tomography, image processing and sinograms constructions have to be further improved, some considerations on the application of this technique to a complex phenomenon, like transient injection of liquids under high-pressure injections, can be drawn.

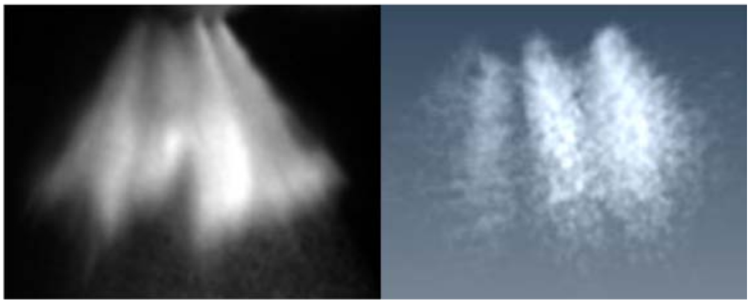

Figure 8 Six hole GDI spray: visible light imaging (left) and X-ray tomography reconstruction (right)

In Figure 8, a comparison between images of sprays, from the same injector and operating at analogues fluidynamic conditions, are reported. They have been captured by elastic scattering of visible light (on left) and reconstructed X-ray tomography (on right). The image on the left is faithful to the real object in terms of contours, details and gray intensity levels proportional to the spatial fuel density. It has been captured at 100 μs from the start of injection with shutter time 1 μs that represents its resolution in time [28]. The jets are recognizable through the different intensities close the nozzle and propagating downstream. Nevertheless the image is bidimensional and all information are integrated on a plane that doesn't allow "to see" the tridimensional structure of the object. On the contrary, the X-ray tomography on the right permits a tridimensional vision of the spray structure. Rotating the reconstruction, the object "is seen" through all the planes, it is possible to enter in the investigated volume and to resolve the projections on a single plane of the information. An evident example is entering in the spray structure and looking the interaction between the jets, where and when it happens due to the respective cone angles interference. Measures of fuel densities and droplet dimensions are possible everywhere in the volume with spatial and temporal resolution, starting from an initial correlation and calibration. The spray behavior can be correlated to the injection parameters like pressure, backpressure and temperature.

The primordial status of the present research activity, the work in progress of the numerical code but mainly the lack of time resolution in the acquisition mode do not permit at this time to exploit all the potentialities of the X-ray tomography technique.

Conclusion

Desk-top X-ray radiography techniques has been used for a tomography reconstruction of a gasoline spray structure. The experimental set-up included a Cu Kα X-ray source, in combination with a polycapillary halflens, coupled with a CCD detector. Two different GDI injectors, mounted on a high-pressure rotating device, $\Delta\theta = 1°$ angular resolution, have been explored at 8.0 MPa injection pressure in a vented Plexiglas chamber. X-ray radiography and tomography reconstruction by sinograms have been made on Cerium additive gasoline sprays. At the present, the investigations have been confined downstream the nozzle tip, around 16 mm^2, with any temporal resolution.

Good reconstructions of the spray structure have been obtained for the six-hole injector with recognition of positions and propagation directions of the six jets. Vision of fuel density and parcel number are possible everywhere inside the spray implying a potential powerful tool to characterize events time-evolving, non-repetitive and at complex fluidynamic structure. Analogue considerations have been reported for a hollow-cone shaped spray. Qualitative considerations of the X-ray radiography and tomography show all the advantages respect to light imaging-based that, more defined and easy to obtain, have the intrinsic limits of the bidimensional flattening.

The experimental apparatus needs further improvements mainly referring to noise suppression, for better sinograms generation, and calibration to give actual dimension to droplets and local fuel densities.

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