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POLYCAPILLARY X-RAY IMAGING OF A GASOLINE SPRAY

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Abstract

Laboratory X-ray techniques based on polycapillary optics have been first used for studying high dense sprays of the jet injection systems. Polycapillary optical elements are well known systems that enable shaping divergent X-ray beams (with energy of up to 30 keV) as well as to get high contrast image of the object studied due to the suppression of multiple scattered part of radiation. We have used a Cu Kα X-ray source in combination with polycapillary halflens (or semilens) and a Photonic Science CCD detector. Due to the low absorption features of gasoline for the used energy range, the images have been acquired in synchronized mode with the spray injection. As a result, it is shown that the absorption signal well emerges respect to the background indicating an interaction of the beam with the fuel.

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1 – INTRODUCTION

An effective air/fuel mixing process is fundamental for a complete combustion in internal combustion (i.c.) engines in terms of exit power and emission pollutant production. In the short ignition delay time before the start of combustion, the injected fuel undergoes to rupture in ligaments and droplets before vaporizing at temperature typical of engines at the end of the compression stroke. The knowledge of the fuel sizes as well as their spatial and temporal distributions is fundamental both for the injection apparatus design and database for the calibration of predictive numerical codes (CFD).

In the last years the technology of internal combustion engines has undergone tremendous improvements in terms of efficiency, consumption and emissions due to the necessity to fulfil the ever more-stringent legislation to safe human health. These processes pass through a deeper understanding of the combustion process in the engine systems whatever during the thermodynamic cycle (Diesel, Otto, HCCI) [1]. The increasing need to understand the air/fuel mixture preparation in the short time before the combustion process has induced the necessity for measurements directly inside the engine combustion chamber in order to follow the different phases of the complex phenomenon of the combustion [2]. Recent technologies for supplying the engine are based on the direct injection of the fuel in the combustion chamber with its atomization, vaporization and mixture with the air in a time having magnitude of tens of microseconds. Thus, characterization of the process is extremely important in order to understand the factors affecting the engine's performances and pollutant emissions [3].

The investigation of the sprays to measure the spatial densities and droplet dimensions is typically carried out by non-intrusive optical techniques using coherent visible light through optically accessible windows. It is a quite complicate matter because the sprays are typically very dense of finely atomized droplets (less than 20-30 μm in diameter) and the incident light experiences multi-scattering phenomena with a negligible output of the beam. Information on the inner structure of these sprays can be obtained at low injection pressures, for wide dispersed sprays and on the boundary of the jets.

The most worldwide used systems to study these phenomena are based on optical techniques for direct imaging of the sprays and their evolution in the engine [4]. Imaging by photographic film or CCD cameras, Doppler-based and extinction-scattering techniques with light in the visible range are widely used in the pre-combustion phase such as the spectroscopic ones in visible-UV wavelength for the combustion/emission analysis [5, 6].

These "conventional" diagnostic techniques, as well as advanced analysis systems like diffraction techniques, exciplex fluorescence and time-of-flight methods [7], are limited by the density of investigated volume. The large number of droplets surrounding or comprising the dense spray core prevents obtaining quantitative data from near-nozzle and central spray regions [8].

Many researchers in this field are directing their activities toward development of high-power laser based techniques to investigate inside these regions while recent interest has growth in non-optical technique, like X-radiography, to penetrate the hard regions of dense sprays and collect quantitative and time-resolved information [7]. X-ray techniques have been used for investigating highly dense sprays because of their weak interaction with the fuel structure chains. No multiple scattering is produced inside the jets and the collected emerging beam provides information on the spray structure, especially concerning the droplet diameters due to high X-radiation penetration.

X-ray studies on the fuel sprays have been performed using brilliant synchrotron X-ray sources [9]. The results indicate a promising way for the characterization of the fuel injection process. Unfortunately, high installation plants and running costs, together with long working time, make the synchrotron source unsuitable for long-term applications.

The use of especially dedicated optical systems can provide rather high flux beams by laboratory X-ray sources. The optimal solution can be realized by the use of polycapillary optics [10, 11]. Polycapillary optical elements allow shaping low divergent X-ray beams (with energy of up to 30 keV) that can be applied for high contrast imaging on fuel jets[12].

In this paper, preliminary investigations on sprays from a Gasoline Direct Injection (GDI) six-hole nozzle by polycapillary X-ray technique are reported. The GDI in Spark Ignition (SI) engines represents an interesting test case and has a practical application in engine technology for both fuel economy and performance improvements. Cu X-ray Source has been used (50 kV, 1 mA, Spot 45x45 μm^2) in combination with half polycapillary lens (focal distance of 91 mm, maximum intensity distance of ~400 mm, transmission of ~60%, residual divergence of ~1.4 mrad). The detector is a Photonic Science CCD (area of 14.4x10.8 mm^2, resolution of 10.4x10.4 μm^2). The images are acquired in synchronized mode with the spray injection, due to the low absorption of X-rays in gasoline in the used energy range. The reported results refer to the sum of 160 images; the total exposure time is 1.6 s.

Moreover, polycapillary optics provides a low divergence beam that was important to improve the image contrast.

The goal of these investigations in the future is to characterize the droplet sizes as well as their spatial and temporal distributions, to define fundamental parameters for the injection system design and database in order to calibrate necessary codes (CFD).

2 - EXPERIMENTAL APPARATUS AND PROCEDURES

2.1. Experimental apparatus

An injection system for spraying gasoline through a six hole GDI injector has been adopted. A hydro-pneumatic pump activated by pressured gas, enabled the injection of the fuel without rotating mechanical pump. Input gas at pressures ranging from 0.07 to 0.7 MPa produced outputs of the fuel at pressures from 2.5 to 25 MPa. A 1.0 dm^3 reservoir pressure tank, located between the injection pump and the electroinjector, absorbed pressure oscillations caused by the fuel delivery.

Pressure transducers allowed monitoring the injection pressure and pressure oscillations just before the injector connection. A six-holes GDI injector, housed in a pressure holder, has been used for spraying the fuel. A Programmable Electronic Control Unit (PECU), is used to control the injector according the set strategies. Figure 1 shows a sketch of the apparatus; further details of the system are described in [13].

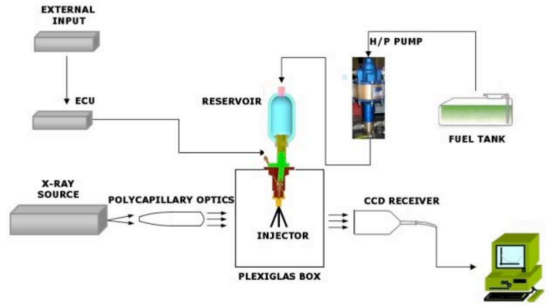

FIG 1 - Experimental set-up.

We have used an Oxford Apogee 5000 tube as a radiation source with a source spot of about 50x50 μm^2, the power of 50 kV and 1 mA. Two kinds of detectors are used: a scintillator (Saint Gobain) with an active area of 2.56 mm^2 and a CCD camera (FDI 1:1.61) with software for X-ray rough/fine imaging. The camera has a sensitive area of 14.4x10.8 mm^2 with a pixel resolution of 10.4x10.4 μm^2. Optical mounts and remote controller actuators designed by Newport are controlled by means of LabView software.

Our prototype for transmission imaging microscope realized at LNF-INFN [15, 16] is used. Half polycapillary lens has been used to converge the beam. This allows getting a very small blurring effect due to rather small radiation divergence behind the optics. As known, each different lens kind provides a residual divergence affecting resolution graduation; if it is supposed that the sample dimension ΔX_0 is reproduced at the detector as ΔX, then the effect can be estimated by

$$|\Delta X - \Delta X_0| \propto l\Delta\theta$$

where l is the sample-detector distance. Therefore, it is necessary to reduce the residual divergence $\Delta\theta$, in order to reach the higher resolution, without changing the distance l.

The used half polycapillary lens has been previously tested and characterized according to a protocol developed at LNF [17] (Fig. 2).

In Figures 3 and 4 the intensity distribution is shown; it is a function of the horizontal axis corresponding to the maximum point value (X axis) and of the distance between the semi-lens and the detector (Z axis). The low value of residual divergence (~1.4 mrad) is evident in Figure 4; the peak intensity at 40 cm from the lens distance is mainly due to the residual divergence.

2.2. Tests and procedures

Experiments have been performed at ambient temperature and atmospheric backpressure injecting the fuel in a chamber under quiescent conditions. The injector is positioned perpendicular to the X-ray beam. The optical path between incident and collected

FIG 2 - Experimental layout for imaging measurements.

X-ray radiation is defined by two aligned windows in the vessel. Kapton sheets covering the test chamber prevent the fuel vapors escape and contamination. The fuel adduction is through a high pressure pipeline; the bottom of the vessel is connected to an exhaust blower to extract the injected droplets under a low velocity air flow. The strategy set on the ECU control is for a single injection, 3.0 ms in duration, with a repetition rate of 3 Hz. The whole system is confined in a cabinet for protection against X-ray radiation.

The focused X-rays meet a spray area of 5 mm downstream from the nozzle. The detection acquisition mode is synchronized with the injection event. A detector exposure of 5 ms covered the entire injection duration. Outside this event the detection system is switched off to avoid background noise accumulation on an intrinsically weak signal.

Due to the low absorption cross-section of the gasoline at 6 keV, doping oil containing 4 and 6 weight % Cerium (Eolys DPX9 Rhodia Terres Rares) is added to the fuel. An absorption increase of 50 % is expected for 4% doping [8].

The absorption of the incident X-ray through the spray is measured by the CCD detector at a repetition of 160 cycles for each condition with a total exposure time of 800 ms.

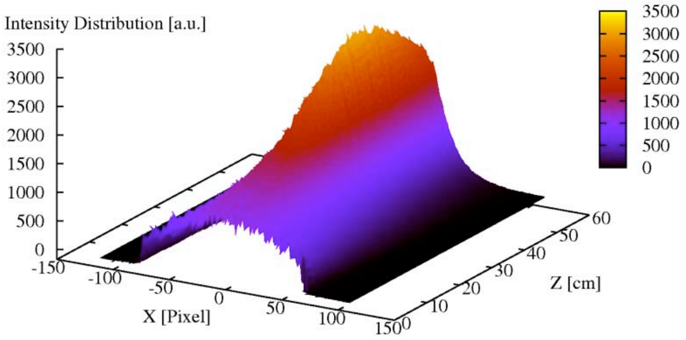

FIG 3 - Intensity distribution obtained by the CCD sensor placed at different distances from the polycapillary optics exit.

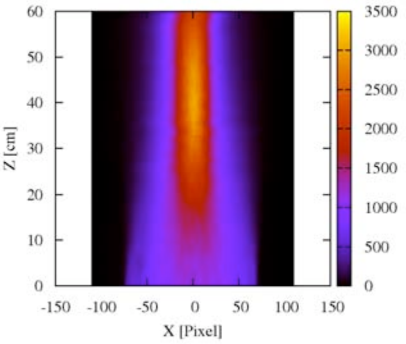

FIG 4 - Contour map of Fig. 3: each pixel has 10.4 μm length on X axis; Z axis has 4 times greater magnitude. A small residual divergence is evident (~ 1.4 mrad).

3 - RESULTS

Table 1 reports the test conditions for the experiments. A GDI apparatus injected commercial gasoline (d=740 kg/m3) in an optically accessible Plexiglas vessel at atmospheric backpressure and ambient temperature.

Table 1: Test conditions

Test Conditions		
Cerium concentration	**4%**	**6%**
Injection Pressure P_{inj}	5 MPa	5 MPa
	10 MPa	10 MPa
		15 MPa
	20 MPa	20 MPa

Two Cerium concentrations have been used to enhance the absorption signals: 4% for injection pressures of 5, 10 and 20 MPa and 6% for 5, 10, 15 and 20 MPa. Due to the X-ray absorption features of the gasoline (typically rather weak at higher energies), it is much efficient to use soft X-rays. In our measurements a bremsstrahlung tail of the spectrum (~ 6 keV) has been used instead of characteristic line for Cu Kα (~ 8 keV). Moreover, measurements at both higher and lower energies were performed but the absorption signals for both cases were too weak; 6 keV was the optimal energy for our studies. Finally, absorption by gas and Kapton windows was measured without gasoline.

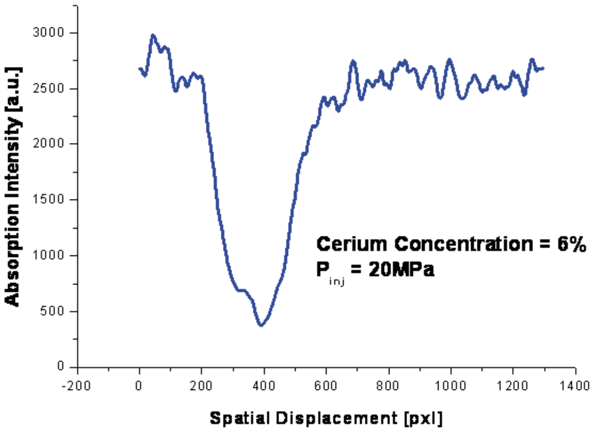

FIG 5 - . X-ray absorption profile through a fuel spray at 5 mm from the nozzle in the spot centre line for 6 keV incident energy.

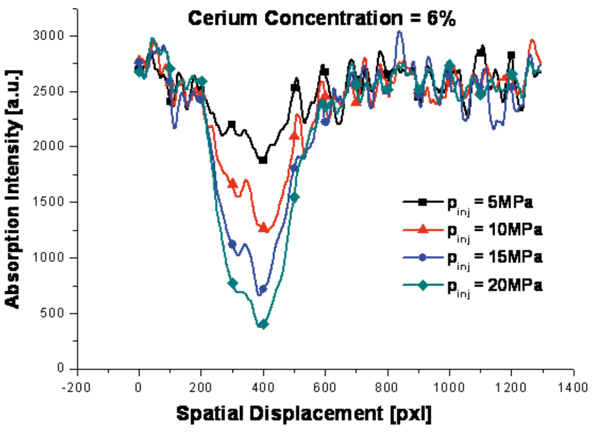

FIG 6 - Absorption comparison profiles of X-ray per different fuel injection pressures at 6% Cerium additive.

In Figure 5 X-ray absorption, along a median line of the spray, is shown for 20 MPa injection pressure and Cerium concentration of 6%. This is the final result of an accumulation of 160 images smoothed and filtered by a low pass filter corrected with respect to the background level. The absorption of the radiation through the gasoline is well defined as the region of highest absorption of about 400 pixels, corresponding to ~ 40 mm. It is not yet known if the asymmetry in the shape reported in Figure 5 is from the focusing setup or fuel density gradients inside the spray.

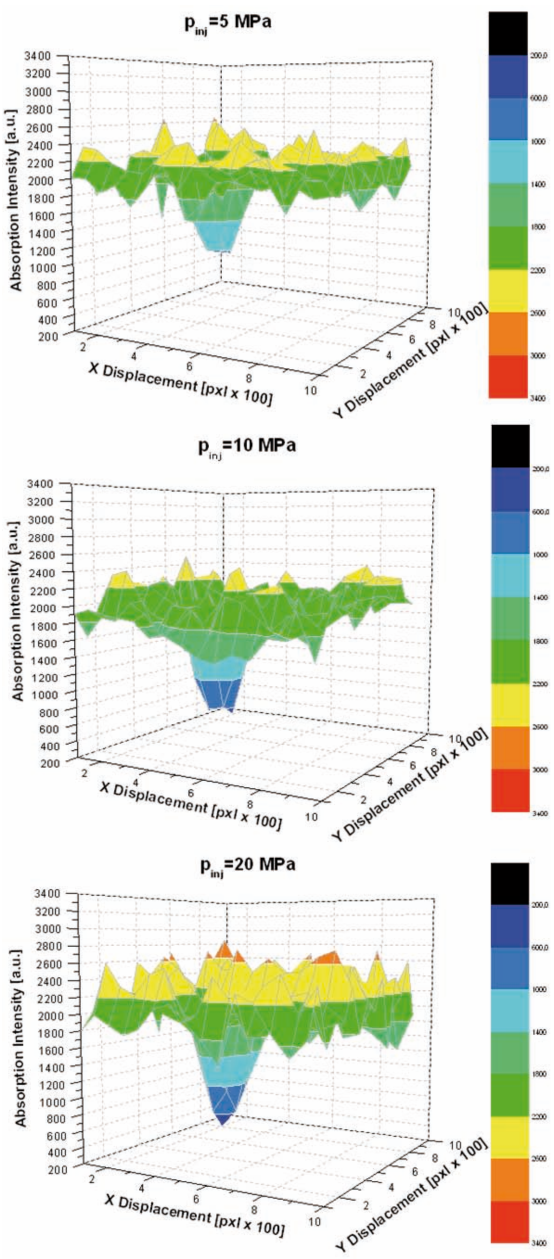

FIG 7 - Two-dimensional sequences of absorption signals at 5, 10 and 20 MPa injection pressures for 4% Cerium additive

Figure 6 displays corresponding absorption curves for different gasoline injection pressures and a Cerium percentage of 6.

The injection duration is constant at 3.0 ms, while the pressure is set at 5, 10, 15 and 20 MPa, with total delivered fuel 29.1, 41.7, 51.7 and 57.7 mg/stroke, respectively. A coherent increase in radiation absorptions versus the injection pressures is evident; the higher the fuel pressure the stronger the absorption of the incident radiation. The intensity profiles have similar minima and are spaced regularly along the y-axis.

Higher injection pressures result in stronger absorption of the incident radiation. The intensity profiles are quasisymmetric respect to a centre line and regularly scaled in values. Two different effects can contribute to this result. First, strongest is the injection pressure highest is the amount of fuel in the probe volume(density) with effects on the absorption of the radiation.
Second, high injection pressures produce fuel clouds more finely atomized. The rupture process of the injected fuel bulk becomes more effective with the pressure gradient across the nozzle. At this stage of the experimental activity it is still unsolved the contribution of the two factors on the absorption curve. Modelling studies by numerical predictive codes are in progress to estimate the influence of the density,

atomization and droplet shape factors on the interaction between the X-ray and the organic chain of the fuel.

Figure 7 shows a plot of a sequence of absorption measurements at 5, 10 and 20 MPa fuel injection pressures with a Cerium concentration of 4 over a 100x100 pixel^2 area.

The absorption increases at increasing pressures and are well above the background absorption. The curves are an average of 160 images of the ratio spray/no-spray acquisitions, subjected to a low pass filter on 25x25 pixels^2.

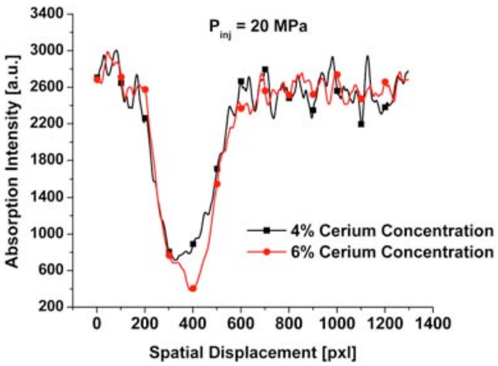

FIG 8 - Absorption intensities for Cerium additive of 4 and 6 %.

The effects of Cerium additive to the fuel sample are shown in Figure 8 depicting increasing absorption properties. Equivalent values are found outside the spray location while, inside the jet, the absorption increases for highest additive values.

The signals have been collected along the spot diameter. No smoothing function has been applied to the graphic.

4 - CONCLUSION

A preliminary X-ray absorption study of highly dense automotive gasoline sprays has been proposed. The weak interaction of X-rays with the fuel structure does not result in strong extinction of the radiation. To maximize the signal absorption, despite of the interaction weakness, we have chosen the best configuration of the experimental setup (polycapillary lens system, Cerium additive oil).

The absorption signal well emerges respect to the background indicating the interaction of X-rays with fuel. The beam extinction is directly proportional to the injection pressure of the liquid and is sensitive to the density in the testing volume and its atomization degree.

Next work to be done is to correlate the absorption intensity and/or the small-angle X-ray scattering figures to the fuel physical and geometrical properties (refractive index, droplet diameter and shape factors). The advantage of the system is that it is based on a table-top setup with a conventional X-ray source, as opposed to being at a synchrotron facility. This reduces costs and optimizes access. Such studies open this methodological approach to new research opportunities.

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