International Journal of Multiphase Flow 70 (2015) 15–21

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

journal homepage: www.elsevier.com/locate/ijmulflow

GDI spray structure analysis by polycapillary X-ray μ-tomography

L. Marchitto [a,*], D. Hampai [b], S.B. Dabagov [b,c], L. Allocca [a], S. Alfuso [a], C. Polese [b,d], A. Liedl [b,e]

[a] Istituto Motori CNR, Via Marconi 8, 80125 Napoli, Italy
[b] INFN – LNF, XLab Frascati, Via E. Fermi, 40, I-00044 Frascati, Italy
[c] RAS P.N. Lebedev Phys. Inst., Nat. Res. Nucl. Univ. MEPhI, Moscow, Russia
[d] Dip. DICMA, Univ. Roma "Sapienza", ViaEudossiana 18, Roma, Italy
[e] Dip. Scienze Geologiche, Univ. Roma3, Largo San Leonardo Murialdo 1, Roma, Italy

ARTICLE INFO

Article history:
Received 20 May 2014
Received in revised form 26 November 2014
Accepted 28 November 2014
Available online 6 December 2014

Keywords:
Polycapillary optics
μ-Tomography
X-ray fast imaging
Fuel injection
Fuel density

ABSTRACT

A X-ray μ-tomography technique, using a Cu Kα source at 8.048 keV coupled with both polycapillary optics and CCD detector, has been developed to reconstruct the composition of a transient gasoline spray generated by a high-pressure GDI injector for automotive applications. The polycapillary elements enable shaping the divergent beams and getting high-contrast images due to the suppression of radiation multiple scattering. A pressure-tight device permits the 360° rotation of a six-hole nozzle, with a step of 0.1°, at injection pressures up to 20 MPa, while the spray plume develops in a vented Plexiglas chamber at the atmospheric backpressure. The entire system is configured as a table-top experiment. The extinction images acquired along the X-ray source-spray-detector line-of-sight have permitted the reconstruction of a 3D structure together with a morphology of the jets within a 3 mm region downstream the nozzle. The spray shape as well as the propagation direction can be clearly identified in the tomographic reconstruction for all the six jets. Quantitative measurements of the fuel mass density in the near nozzle region have been performed. Typical Gaussian-shape distribution of the intensities appears for the cross sections revealing the more dense jet regions in the core, while slight longitudinal asymmetries indicate an interaction between the jet plumes.

Introduction

The increasingly stringent environmental regulations of transportation pollutant emissions require the development of advanced technologies for fuel efficiency improvement without compromising the brake power. The direct injection of gasoline (GDI) in spark ignition engine plays a key role for this target.

At first, GDI systems were introduced to improve thermal efficiency and power output (Park et al., 2012; Najjar, 2011; Zhao et al., 1999). The direct fuel injection allows a more accurate control of the injection rate than the Port Fuel Injection (PFI), with a consequent reduction of the combustion cycle-to-cycle variations. The higher injection pressure induces a better atomization with the improvement of the vaporization rate, increasing the volumetric efficiency in the cylinder. Moreover, the direct injection of the fuel into the combustion chamber avoids that part of fuel to impact directly on the intake port wall and the valves leading to a potential reduction of the unburned hydrocarbons. On the contrary, the reduced time for the air–fuel (AF) mixing inside the combustion chamber could induce an increasing particulate matter and unburned hydrocarbon production due to the combustion chamber wall impingement phenomena.

Nowadays, the interest for Spark Ignition Direct Injection (SIDI) engines is focused on the possibility to perform lean combustion providing significant fuel economy benefits with respect to the conventional PFI engines. A theoretical reduction up to 25% of the fuel consumption by using the GDI engines is estimated (Zhao et al., 1999; Alkidas and Tahry, 2003; Chitsaz et al., 2013). Maximizing the AF ratio the lean combustion could be achieved with stratified charge mode where rich mixture is present close to the spark plug, while the remaining volume is filled with a lean one. The limits of this process are defined by too lean mixtures that could lead to the unstable combustion lowering the flame speed and inducing partial burning events. Hence, an accurate control of both fuel spray development and air fuel mixing is crucial to fully exploit the potentialities of the direct injection in the spark ignition engine (Lee et al., 2013; Heywood, 1988; Zhao and Ladommatos, 2001).

Experiments on the sprays for automotive applications are generally performed by means of non-intrusive diagnostic techniques to not interfere with the process. Typically, conventional optical

* Corresponding author. Tel.: +39 0817177119; fax: +39 0812396097.
E-mail address: l.marchitto@im.cnr.it (L. Marchitto).

http://dx.doi.org/10.1016/j.ijmultiphaseflow.2014.11.015
0301-9322/

techniques using light sources from near ultraviolet (UV) to infrared (IR) wavelength region (~180–900 nm) are applied (Linne, 2013). Global morphology measurements concerning both liquid and vapor phases of the jet can be obtained. Mie scattering technique coupled with high speed cameras allows characterizing the main jet geometric parameters such as the tip penetration and the cone angle (Payri et al., 2013). The vapor phase is investigated through refractive-index gradient-based techniques such as shadowgraphy and schlieren (Chitsaz et al., 2013; Klinner and Willert, 2012). These provide useful information about the vapor–liquid fraction and their time evolution. Moreover, the density of the spray could be theoretically estimated. Quantitative measurements are prevented due to the high dependence of the measurements on the refractive index gradients that strongly reduce the Signal to Noise Ratio (SNR). Furthermore, there are strong limitations concerning the inner structure investigation due to the high fuel density near the nozzle and in the core of the jet. In these areas both absorption and multiple scattering effects of the incident light prevent this approach restricting it to low-dense areas typically surrounding the spray.

Measurements on the internal features of a spray are fundamental to characterize the break-up of the fuel occurring at the nozzle exit and influencing the whole spray development. Currently this kind of information is approximately determined through computational fluid dynamic (CFD) approaches which describe the spray formation only after the primary break up when the inner structure is featured by few microns droplets (Costa et al., 2012).

Phase Doppler Anemometry (PDA) and Laser Doppler Velocimetry (LDV) can supply useful data about both velocity and size of the droplets just in the dilute regions of a spray, typically, on the boundaries of the jet or far from the nozzle (Aleiferis and van Romunde, 2013; Allocca et al., 2009). Recently, Linne et al. (2009) successfully applied ballistic imaging to get high-resolution, single-shot images of the liquid core of a dense sprays featuring jet structure and morphology, droplet ruptures.

However, while conventional optical techniques can provide information about the liquid, the vapor phase structures and the liquid break-up, they are not efficient for the quantitative measurements of local fuel densities. This lack of data can be integrated through X-ray measurements; because of the weak interaction of X-radiation with the fluids, the radiation can penetrate their structures and provide spatially-resolved information along the propagation direction (Halls et al., 2012; Heindel, 2011; Halls et al., 2014).

First studies concerning dense sprays investigation by means of X-ray absorption techniques date back to the 80's. In 1984 Gomi and Hasegawa (Gomi and Hasegawa, 1984) estimated the mass distribution of the liquid phase in a water/gaseous nitrogen spray by the X-ray absorption method. Recently, Synchrotron Radiation Source (SRS) absorption-based techniques have been applied to investigate high-dense regions of the fuel sprays providing quantitative measurements of the fuel mass (Im et al., 2013; Kastengren et al., 2008). X-rays penetrate the dense part of fuel spray because of their weak interaction with the low Z hydrocarbon chain. X-ray radiography and tomography have been used to investigate the core of gasoline and diesel sprays and to reconstruct the three-dimensional (3D) structure. SRS are high-brilliant sources providing monochromatic and collimated radiation beams with pulsed structure at high frequency.

The portable X-ray sources are discarded with respect to SRS because of their lower energy, high divergence and time-continue structure (Kak and Slaney, 1999). Recent progresses in advanced optics for X-ray applications such as polycapillary lenses have allowed to overcome some of these limits permitting high-intense quasi-parallel beams with a ~60% transmissivity to be obtained and high contrast images to be acquired (Hampai et al., 2009b; Kumakhov and Komarov, 1990; Dabagov, 2003; MacDonald, 2010).

X-ray transmission through polycapillary optics is based on the phenomenon of Total External Reflection (TER) of radiation by a surface. Any X-ray photon impinging on the channel's wall (typically of glass composition) at an incidence glancing angle lower than the Fresnel angle θ_c (the critical angle of TER) propagates along the channel by multiple reflections. The number of reflections can vary from one to a few tens and even hundreds, that is why this optics is called multiple reflection optics. Due to the following features: (i) rather wide acceptable requirements for the source parameters (from conventional X-ray tubes up to synchrotron radiation sources); (ii) high efficiency of radiation bending through large angles (up to 30° at 10 15 cm); (iii) possibility of increasing the radiation density (up to 10^4 times); (iv) a broadband spectral working regime (from about 1 keV up to 50–70 keV) – these optical devices are more suitable for instrumental applications and development based on X-ray diffraction, fluorescence and imaging.

The present study reports measurements results on transient jets structure by means of a top-table apparatus using a portable X-ray source coupled with a polycapillary semi-lens. Three-dimensional tomography (3D CT) of GDI sprays have been realized performing accurate fuel mass density measurements in a region very close to the nozzle exit.

Experimental setup

To determine the inner structure of dense sprays coming from a GDI 6 hole injector the X-ray tomography technique has been applied.

The X-ray acquisition setup has been designed and developed at the XLab-Frascati of Laboratori Nazionali di Frascati (LNF) (Hampai et al., 2009a). An Oxford Apogee Cu Kα X-ray tube (voltage 30 kV, current 1 mA) with a focal spot size of about 50 μm was used, coupled with a polycapillary semi-lens with a transmissivity of 60% for Cu X-rays and a residual divergence of about 1.4 mrad to obtain a quasi-parallel beam. This configuration allows a strong reduction of the blurring effect avoiding diffraction effects on the sample edges as well as multiple scattering radiation in the matter (Hampai et al., 2011). A Photonic Science CCD camera (FDI 1:1.61 (FDI, 1985)) with a sensitive area of $14 \times 10\ \text{mm}^2$, pixel size of $10.4 \times 10.4\ \mu\text{m}^2$, and 12 bit image digitalization was used. The CCD detector has been synchronized via external trigger with the injection events. The spatial resolution was found to be 16.67 μm/pixel (Hampai et al., 2013; Allocca et al., 2012). A home-made LabView code controls the synchronization among injection system, CCD detector and stepper motor. A set of 100 injection event and background images has been acquired for each angular step.

The injection apparatus consists of a pneumatic pump activated by a pressured gas, a multi-hole injector for gasoline direct injection and a programmable electronic unit for pulses control. For gas pressures ranging between 0.07 and 0.7 MPa the injection pump delivers fuel at 2.5–25 MPa. Commercial gasoline ($\rho = 740\ \text{kg/m}^3$) blended with an additive containing Cerium 4% in volume (Eolys DPX9 – Rhodia Terres Rares) was used to enhance the low absorption cross-section (Hampai et al., 2013; Allocca et al., 2012). The spray has been injected at 12.0 MPa pressure and 4 Hz frequency in a transparent Plexiglas vessel at atmospheric back-pressure and ambient temperature. The doped oil was delivered by a solenoid-actuated 6 hole GDI injector (0.193 mm hole diameter). A typical commercial multi-hole injector for automotive application has been chosen, although the structure of the jets could complicate the experimental set-up. In fact, a multi-hole injector provides interacting jets along their development with an atomization process higher than the single-hole nozzle with same injection rate.