Table-top flash X-ray diagnostics of dodecane sprays

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Abstract

Time resolved radiography of pure dodecane and cerium doped dodecane sprays expanding through micrometric nozzles in a high pressure injection chamber inflated up to 30 bar have been performed for the first time using a table top flash X-ray source. The radiograph analysis indicates that strong mixing between liquid and ambient gas occurs in the very near nozzle region. The spray is described as two different density components having different penetration velocities which amplitudes also depend on the chamber pressure.

Introduction

The development and optimization of diesel engines faces many critical issues related to the search for the most efficient combustion conditions and the limitation of soot, CO_2, NO_x, and unburned hydrocarbons byproducts emissions. Apart from the recent studies dedicated to the development of new "biodiesel" fuels, conventional diesel engines have been operated with higher and higher rail pressures to enhance the liquid spray evaporation. This progressive change in the engine working conditions has required both experimental and modeling efforts for the design and characterization of new injection strategies (injector design, injection duration or frequency), combustion chamber, etc. Significant progress have been achieved, essentially through high speed shadowgraphy or laser based diagnostic techniques such as LIF, LDA, PIV, etc., developed for the spray characterization in connection with modeling works. Unfortunately, the visible or UV light scattering in the dense near nozzle region consists in an intrinsic limitation preventing to obtain valuable experimental data in this specific zone. The unique non intrusive experimental technique reported up today to get a comprehensive description of the near nozzle spray behavior is based on the soft X-ray absorption, such diagnostics being essentially developed at Argonne National Laboratory using synchrotron X-ray at the Advanced Photon Source [1]. Following our previous experiments on the development of flash X-ray diagnostics [2] and cryogenic nitrogen jets at supercritical pressures X-ray characterization [3], this contribution deals with the time resolved diagnostics of dodecane injection through micrometric nozzle in a high pressure chamber, using a table top lab developed flash soft X-ray source. While providing much less accurate data than highly monochromatic and space resolved synchrotron studies, time resolved, on nanosecond time scale, flash X-ray radiography allow for the determination of the near nozzle spray density together with the spray angle and propagation velocity in a large range of operating conditions including different injectors, chamber pressure, rail pressure, and fuel composition.

Materials and Methods

The sprays are generated through Bosch serial vehicle injectors having six holes, 150 µm in diameter, the rail pressure ranging from 400 to 1200 bars. Both pure dodecane and dodecane mix with Rhodia DPX9 diesel fuel additive in a 0.5% volume fraction have been experienced and compared in term of the spray characteristics using the same injectors. The injector nozzle is set in a 1 dm3 high pressure chamber filled with nitrogen from atmospheric pressure up to 30 bars. Two rectangular slits (5mm wide, 24 mm high) equipped with a 125 µm thick kapton® film, presenting a high X-ray transmission, are used as entrance and exit windows along the X-ray propagation path from the X-ray source to the Andor DY432-FI-DD X-ray camera. The flash X-ray source consists in an evacuated X-ray tube, equipped with a carbon annular cathode and a brass rod anode, powered from a Blumlein like pulse forming network including a low jitter thyratron switch and delivering high voltage pulses, 30 kV in peak amplitude and 30 ns long. The X-ray emission spot is set at 80 cm from the nozzle axis and the X-ray CCD sensor is located 10 cm behind the nozzle axis. Spectroscopic measurements reveal that the X-ray emission consists in a weak Bremsstrahlung spectrum extending up to 30 keV over which an intense emission in the copper characteristic lines at 8 keV superimposes. Transmission measurements in a large variety of samples, including objects having thickness down to a few tens of microns and density close to that of dodecane (0.8 $g.cm^{-3}$), have been performed to determine a 8,3 keV average X-ray spectrum energy. This average X-ray energy approach was inspired from the work of Curry [4], showing its relevance for the determination of sample density using non monochromatic X-ray source. The injector pilot controls the injection duration, the rail pressure and provides a trigger signal for the flash X-ray source with a variable delay between the injector needle activation

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and the high voltage switch. X-ray radiographs are obtained by averaging over up to 4000 X-ray shots, 20 ns in duration, for pure dodecane sprays and over up to 1000 shots, 20 ns in duration, for DPX9 doped sprays, to achieve a significant contrast and a sufficient signal to noise ratio, between the spray and the nitrogen absorptions.

Results and Discussion

Experiments using caviting and non caviting injectors (ks0 and kf1) have shown similar behavior of the spray expansion. The same holds true for whether pure dodecane or mix of DPX9 with dodecane sprays. The spray density is inferred from grey level profiles extracted from the X-ray radiographs and the Beer Lambert x-ray absorption law considering a 8,3 keV mean cross section. For all experimental conditions used in this work, the spray density at the nozzle outlet never exceeds 0.3 g.cm^{-3} indicating that no so-called pure liquid core exists in the near nozzle region but that significant mixing with ambient nitrogen occurs, the liquid fraction representing less than 40%. A continuous decrease of the spray density along its penetration path was measured over the first 15 mm downstream the nozzle outlet. The spray geometry was measured to be very reproducible from a few hundreds to a few thousands of injection events, the angular aperture being of about 5° over the first 15 mm. The sprays exhibit two distinct components, a high density region in the near nozzle region and a much lower density structure downstream the previous one as depicted in figure 1. It also appears that the lower density component has a higher velocity than the near nozzle component as illustrated by the full and dashed lines in figure 1 which correspond respectively to a mean velocity, from the start of injection to 90 µs later, of 35 m.s^{-1} and 125 m.s^{-1}. The spray leading edge mean velocity measured between 40 and 90 µs after the start of injection was shown to decrease from 255 m.s^{-1} to 213 m.s^{-1} and 138 m.s^{-1} when the nitrogen pressure in the injection chamber increases from 1 to 13 and 25 bars respectively.

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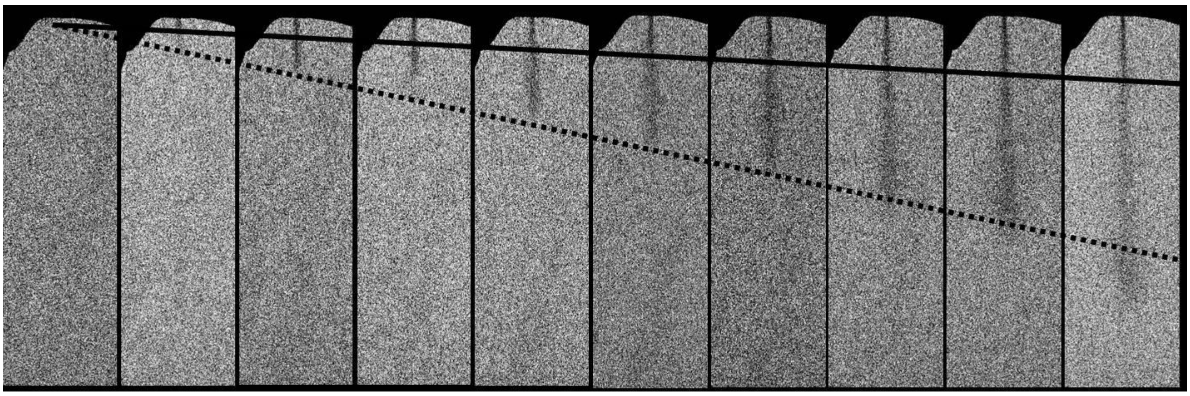

Figure 1. Expansion of a dodecane spray through a nozzle having holes of 150 µm in diameter. The rail pressure is of 800 bar and injection duration of 500 µs, the injection chamber is filled with one bar of nitrogen. Each radiograph is averaged over 1000 injection events. The time increment between each radiograph is of 10 µs from start of injection on the left to the righter picture 90 µs later for which the jet expands over 14 mm.