Fuel 153 (2015) 183–191

Contents lists available at ScienceDirect

Fuel

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

Transient characteristics of diesel sprays from a deposit rich injector

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HIGHLIGHTS

- Deposit rich diesel fuel injectors produce fuel sprays rich in anomalous transients.
- These transients show an increased radial fuel momentum at the cost of axial momentum.
- These transients lead to a low fuel spray reproducibility from injection to injection.
- A liquid back pressure medium allows studying anomalies on a prolonged time-scale.

ARTICLE INFO

Article history:
Received 3 December 2014
Received in revised form 24 February 2015
Accepted 25 February 2015
Available online 7 March 2015

Keywords:
Diesel sprays
Fuel spray evolution
High speed imaging
Fouled injector
Transients
Injection in liquid

ABSTRACT

The transients of the early stage evolution of high pressure diesel sprays from a clean and a deposit rich injector were explored using high speed imaging at 24.4 kiloframes per second (kfps). Fuel was injected into a liquid that offered high density ambient conditions and, for comparison, fuel was also injected into air at less dense ambient conditions. By comparison of the evolving fuel spray from a new fuel injector to those of an injector rich in carbonaceous deposits at/in the nozzle, anomalous spray behaviour resulting from the presence of deposits becomes apparent. The fuel spray cone angle from a deposit rich injector increased by 10–140% compared to the fuel spray cone angle from a new injector. The accompanying spread in the measured angle was from 100% to 200% greater for the deposit rich case. The presence of deposits significantly affected the early stages of spray evolution, the reproducibility of the spray shape from a deposit rich injector being very low. The observed occurrence of transient radial bulging has the potential to reduce the axial momentum and reduce the combustion performance in diesel engines.

1. Introduction

The proposed stringent emission regulations have imposed a strong motivation on automotive and fuel companies to improve the in-cylinder processes to reduce emissions of diesel engines. The most recent advances in diesel engines include, amongst others, the use of higher injection pressures, smaller orifice diameters and multiple-injections schemes. These advances are primarily geared at increasing the combustion efficiency by optimizing the air–fuel mixing, ignition and burn characteristics. As these characteristics in turn are highly dependant on the dynamics of fuel spray momentum and air entrainment, a major part of contemporary diesel spray research focusses on imaging fuel sprays and analysing both how the fuel spray evolves during injection and how the ambient conditions, injector nozzle geometry, and injection parameters influence spray dispersion [1,2]. To this end a fuel injection event is illuminated, or made to fluoresce, by a pulsed LASER system synchronized with a camera [3,4] or direct illuminated by an arc light, either continuous or pulsed at low repetition rates, in combination with a high speed camera. Macroscopic parameters such as spray cone angle, penetration length, atomization and evaporation of a fuel jet were explored to qualitatively estimate the efficiency of the combustion process [5,6], several optical methods and analysis have been used extensively over the past decades in diesel engine research and these methods have been treated in several reviews [7–9], while the techniques used for imaging optically dense regions of fuel sprays have been discussed in [10].

Although the optical investigation of fuel spray evolution is widely used to determine spray characteristics of fuel injectors and nozzles, the spray shape evolution resulting from deposit rich injectors is investigated only sporadically [11]. Most studies are directed at investigating the effect of carbonaceous deposits on the engine performance and combustion quality by monitoring

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http://dx.doi.org/10.1016/j.fuel.2015.02.114
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macroscopic parameters, for example fuel economy or engine power loss, and correlate these to the amount and types of deposits present on/in the injector [12,13], where often deposit formation is ensured by adding metallic salts to the fuel that enhance nozzle coking [14,15]. These methods are well-suited to determine the parameters that enhance deposit formation and the effect of deposits on overall engine performance. However they do not directly provide any fundamental insight on the processes through which combustion degradation results from the presence of deposits on/in the injector nozzle.

In this work we have made attempts to explore the direct effect of deposits on spray structures by investigating the early stage evolution of diesel fuel sprays. Transient changes of the spray shape were studied by comparing the details of injection events from a deposit rich injector to that of a new injector.

2. Experiments

In this study the primary interest lies in acquiring a more fundamental understanding of how deposits on/in the diesel injector nozzle affect the early stage transients of spray evolution. The experimental arrangement used for imaging spray evolution consisted of a minimized set-up which offered good optical and physical access for applying modifications, most notably replacing the injector in a short timespan. To this end a novel experimental set-up incorporating a liquid back pressure medium and LEDS in a front-lit configuration was used. The schematic of the experimental set-up is depicted in Fig. 1. In this set-up diesel was injected in a glass tank which was filled either with air or water. With these injection media, the equivalent chamber densities were 1.2 kg m^{-3} or 10^3 kg m^{-3} respectively. The typical densities in an engine cylinder are of the order of tens of kilograms per cubic meter, and in this work it is assumed there is no loss of generality when studying the near nozzle spray evolution whilst using air and water as injection media. It should however be noted that this applies only to pressure and density related phenomena, such as spray evolution and penetration. Effects depending on the spray-gas interaction and fuel chemistry under engine like ambient conditions, i.e. evaporation and combustion, can not be studied using a liquid back pressure medium.

Diesel spray evolution studies incorporating a liquid back pressure medium have been conducted previously, for example to study chamber geometry effects in [16] or, more recently, to study jet instabilities in [17]. These studies generally look at the macroscopic atomization cloud extending downstream distances on the order of centimetres from the nozzle. The investigation presented here however focusses on the near nozzle, early evolution of the diesel spray (distances up to 3.6 mm from the orifice) and any anomalous behaviour resulting from the presence of deposits in the injector.

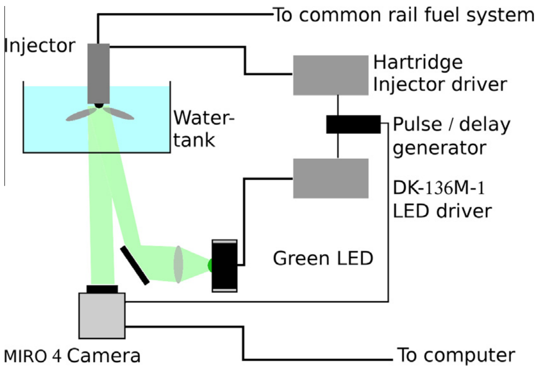

Fig. 1. Experimental arrangement used for imaging the evolution of diesel sprays.

2.1. Fuel injection

A common-rail diesel injector with six orifices was used at an injection pressures of 40, 60 and 80 MPa. The injector was driven by a HARTRIDGE injector driver which, through external triggering, was set at short single-shot injections of 0.58 ms duration, as we were investigating only the early stage of spray evolution. Commercially available red diesel was used in this investigation.

For the comparative study of the effects of deposits on the fuel spray evolution, two different injectors were used. A new injector was used as a base injector, producing highly reproducible spray shapes with minimum anomalies. This injector is referred to as the *new* injector throughout this article. The second injector, of the same type number, had carbonaceous deposits at the tip of the nozzle and general signs of wear due to its near end of life operation, and is henceforth referred to as the *deposit rich* injector.

2.2. High speed imaging

For the imaging of spray evolutions, a VISION RESEARCH PHANTOM MIRO 4 camera was borrowed from the EPSRC Engineering Instrument Pool for the duration of this project. The MIRO 4 is capable of imaging in different modes, ranging from 800 × 600 pixels at 1250 fps up to 111 kfps at 32 × 16 pixels, decreasing the image size with increasing frame rates. As a trade-off between quality and frame rate the camera was used at a frame rate of 24,390 fps with a resolution of 128 × 128 pixels, where the high back pressure of the liquid injection medium led to sufficient deceleration of the fuel jet to allow imaging the fuel spray evolution without visible motion blur. For injections in ambient air some motion blur occurred at this frame rate, but it was considered acceptable as this data was only used for qualitative comparison to the injections analysed at higher ambient densities.

2.3. LED illumination

For the illumination of the evolving diesel fuel spray, a PHLATLIGHT CBT-120 high power green LED was used as a light source in a front-lit configuration throughout this experiment. Although LED light sources have been successfully used in different fields of study, including combustion research [18–23], they are not used in a front-lit configuration for illumination of short lived transients occurring during fuel injection. When looking at available articles on research involving high-power LED sources [24,25], it can be seen that contemporary LEDS that allow high-current pulsed operation should however be capable of producing pulses suitable for spray imaging. As in these experiments good (physical) accessibility and ease-of-use of the injection chamber was required, illumination using a pulse operated high powered LED was strongly favoured over the use of a LASER system. Additional advantages of using LEDS as an alternative to LASERS for high speed imaging of sprays and in combustion research, have been treated in [26,27].

In this research the LED was pulse driven with a pulse width of 2–4.5 μs and repetition rate of 24.4 kHz. At a total illumination time of 2–4.5 μs the LED allows a duty cycle of 50% at the current densities used in this research, and a theoretical frame rate of 111–500 kfps would be possible with this LED as an illumination source, provided the corresponding camera would be capable of recording at this frame rate.

3. Measurements and results

Series of images were acquired of different diesel injection events in water and in air under atmospheric conditions, using