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Spatio-temporal evolution of diesel sprays at the early start of injection

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HIGHLIGHTS

- Used injectors produce high spray penetration variations at the start of injection.
- The penetration variations are worse for older, higher mileage, injectors.
- Reduced spray penetrations are accompanied by anomalous radial expansions.
- The radial anomalies lead to fuel-rich vapor pockets that remain close to the nozzle.

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ABSTRACT

The impact of injector life on the spatio-temporal evolution of fuel spray quality was optically investigated using high speed imaging techniques. Both new and used injectors, which had been used in intense operation for up to 90,000 miles, were considered in this investigation. Used injectors are prone to wear, deposit formation, and altered internal nozzle flow. High resolution SEM images clearly portray the presence of carbonaceous deposits both at the injector tip as well as within the holes of used injectors. Investigations revealed that used injectors tend to produce a chaotic hole-to-hole variation at the start of each injection, resulting in an asymmetric early fuel spray penetration pattern in the first 500 µs. Often those sprays that suffered a reduced spray tip penetration rate at the start of injection also showed off-axis transient expansions, and those sprays appeared to be bulky compared to other sprays. Following the early asymmetric spray penetration phase of injection the retarded sprays undergo rapid acceleration with time, and this transformed the early asymmetric spray pattern into a nearly uniform spray pattern from all the orifices in the quasi-steady state regime. The hole-to-hole penetration variations and the resultant asymmetric spray structure at the early start are therefore short lived transient phenomena. However if the radial expansion of the spray is large during the early phase, the radially expanded plume remains almost at the same radial location due to lack of local axial momentum, even after different time instants of spray tip propagation. This appears as a bulge to the spray and can eventually end up as a stationary local pocket of fuel vapor close to the nozzle for the entire duration of injection. This may alter the ignition, flame lift-off and entrainment characteristics of sprays injected from used or deposit rich injectors.

1. Introduction

Reducing the engine-out soot and NO_x to ultra-low levels has been a strong motivator to explore into the in-cylinder processes through optical diagnostics in diesel engines. As a result an increasing amount of research is being carried out to enhance the understanding of air utilisation in diesel sprays, and this has led to both microscopic and macroscopic research on sprays to study its break-up, evolution, dispersion, evaporation, and ignition [1,2]. It has been shown in [3,4] that by controlling the fuel injection system parameters precisely, and by having well-targeted sprays, the air utilisation can be improved which has the potential to reduce the soot formation and its oxidation in diesel spray flames. Since the global characteristics of sprays are influenced by the fuel properties, more attention has been devoted to investigate the effects of fuel viscosity variations due to emulsification [5], fatty acid compound variations [6] and for fuel blends having a widely varying distillation range [7], as the spray formation remains equally important compared to different chemical compositions in order to mitigate emissions from diesel engines. The evolution of fuel sprays are also strongly controlled by the nozzle internal geometry, in [8] both the macroscopic spray formation and the internal nozzle flow of several biofuels have been compared to those of mineral diesel.

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These investigations are continuously leading to the development of a more advanced and complex injection system with improved spray characteristics, however most of the spray research work is focussed on the behavior of new or research-grade injectors instead of used injectors. It is also well-known that diesel injectors suffer from deposit formation at the tip of the nozzles due to its normal use in an engine under high temperature conditions. The impact of coked nozzles on engine efficiency, fuel consumption, and engine emissions have been researched extensively in [9,10]. Recent work on the optical investigation of sprays from fouled injectors, and a review of the effect of nozzle deposits on emissions and on spray evolution can be seen in [11], whilst [12] optically investigated the combustion characteristics from a fouled injector. Additionally, the amount of work conducted on the optical investigation of the very early (transient) spray evolution using modern measurement techniques allows the recording of the early transient phase with an unprecedented image quality, as can be seen in [13–15], where investigations are generally conducted using a single-hole research-grade injector or a brand new production injector.

Recent investigations have shown that post injection dribble or expulsions is becoming an important issue, as it contributes to additional engine out soot and UBHC emissions [16,17]. Multiple short injection strategies are slowly replacing the single injection operation in modern diesel engines; early spray evolution, dispersion and ignition of second, third or subsequent injections can be impacted by the post injection dribble/expulsions of the earlier injection [18,19].

Recently we have optically investigated the differences in fuel spray evolution and dispersion of a new multi-hole diesel injector, comparing it to an end-of-life injector. The latter injector produced clearly discernible transient anomalies that were absent for the new injector, when the fuel was injected into a very high density ambient environment [20].

In this paper we present the results of an extensive evaluation of the early spray evolution from thirteen multi-hole diesel injectors that were in operation in passenger cars on the UK roads for up to 90,000 miles. This early spray evolution was investigated in an optically accessible constant volume high pressure chamber, where the operating ambient densities selected for our investigations were comparable to the conditions of HSDI diesel engines. It will be shown that transient characteristics occurring at the very early start of spray formation differ strongly for used injectors when compared to new injectors. Depending on the history of the injector, not all injectors showed the same severity of transients at the early start of injection. However there is a tendency for used injectors to show a progressive spray quality degradation and an increase in severity of early transients over the lifetime of the injector.

2. Experimental conditions

A similar investigation of the effects of injector deposits and/or wear on the evolution of the fuel spray has been conducted previously in a high density ambient environment [20], where the transient spray anomalies became clearly visible in the presence of a high density ambient medium. Although from a fundamental point of view these observed anomalies can teach us a lot on the effect deposits have on fuel sprays, it was not clearly known how our observed anomalies under extremely high density conditions in [20] translate to the fuel spray behavior under real-world engine operating conditions. In the present investigation the charge in a constant volume chamber (CVC) was maintained at a realistic engine compression-pressure environment, by using a compressed heated inert gas. Evaporation and subsequent combustion of the injected diesel fuel spray was inhibited in this research, as rapid evaporation of the atomised stage would lead to the loss of visibility of spray evolution, and it is precisely the liquid fuel spray evolution that is under investigation in this research.

The experimental set-up is schematically depicted in Fig. 1. Main parts of the set-up are treated briefly in the following sections, Table 1 provides an overview of the main experimental parameters as applied in this research. A more detailed description of the set-up can be found in [17].

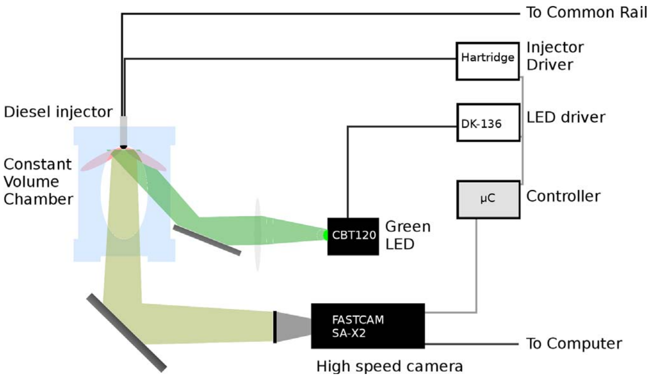

Fig. 1. Schematic of the experimental set-up as applied in this study.

Table 1
Experimental parameters applied in this research.

Parameter	Setting
Injectors	13 pcs, 6-orifice nozzle, common-rail, solenoid actuated
– Conditions	new(2), 30 k-mile(4), 63 k-mile(4), 92 k-mile(3)
Injection pressure	80.0 MPa
– Duration	1.46 ms
Ambient medium	gaseous N_2,>99% purity
– Pressure	3.3 MPa
– Temperature	112–118 °C
Recording frame rate	45 kfps
– Inter-frame time	22.2 μs
– Exposure	2.5 μs
Illumination wavelength	521 nm
– FWHM	40 nm
– Duration	2.6 ms
Image scale	77 μm/px
– Size	39×39 mm^2
– Pixels	512×512 px^2

2.1. Constant volume chamber

Measurements were conducted in a CVC, designed and manufactured specifically for imaging diesel fuel injections under varying back-pressure conditions, allowing maximum continuous back-pressures up to 8.0 MPa. Cartridge heaters in the body of the CVC allowed heating up to 145 °C for any gaseous medium, and was primarily incorporated to minimize condensation of injected diesel on the interior of the chamber. With the help of acetylene pre-combustion, chamber temperatures could be raised to approximately 1500 K momentarily, with the chamber tested and certified to withstand peak pressures from pre-combustion up to 12.0 MPa. The investigation treated in this article was conducted without the application of pre-combustion: As we were primarily investigating transient anomalies occurring at the very early start of injection, backscattered light off the non-evaporated fuel spray was measured. The CVC was heated to 112–118 °C, high enough to prevent condensation of diesel on the windows and low enough to prevent rapid evaporation of the atomized droplets. The ambient conditions provided a non-reactive background of pure (>99%) nitrogen, which was allowed to reach thermal equilibrium with the steel body of the CVC at 112–118 °C to minimize convection inside the chamber. Back-pressures were maintained at 3.3 MPa which, at an average temperature of 114 °C would provide an ambient density of the same order of magnitude as inside a diesel engine.