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Combustion of ligaments and droplets expelled after the end of injection in a multi-hole diesel injector

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HIGHLIGHTS

- Both new and used injectors expel liquid fuel post-injection in a random manner.
- The amount of fuel expelled is independent of injector age/mileage.
- The expelled ligaments and droplets remained visible up to 25 ms after EOI.
- In a constant volume chamber these expulsions will continue combustion long after EOI.

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ABSTRACT

Experimental investigations were carried out to study the end of injection spray characteristics using a number of multi-hole common-rail production injectors. These injectors were taken from light-duty diesel vehicles that are currently in operation on the UK roads and have done different mileages. All the production injectors suffered expulsions of ligaments and droplets after the end of injection (*a*EOI). It is shown that injector age/mileage has very little effect on the amount of expulsions compared to injection-to-injection variations in the amount of post-injection expulsions. Brand new production injectors also show the presence of these post-injection expulsions after every injection, which is not a desired feature of the modern solenoid actuated common-rail fuel injection system. Subsequent combustion of these post-injection ligaments and droplets lasted up to 25 ms after the end of fuel injection in our high pressure, high temperature experiments, and this would contribute to engine-out soot and unburned hydrocarbon (UBHC) emissions in a firing engine.

1. Introduction

In order to meet the current and future emission regulations, diesel engines are fitted with exhaust after treatment devices to reduce tail-pipe emissions of soot and NO_x. The load on these after treatment devices could be reduced if engine out NO_x, soot, and UBHC emissions could be better controlled. There is a greater need to understand the in-cylinder processes to further improve the fuel spray mixing processes and the accompanying combustion and emission formation. Much of the research is aimed at studying how combustion can be optimized, and emissions minimized, through optimizing fuel spray patterns and injection strategies [1–3], a recent example of research into the effect of end-of-injection rate shaping on combustion recession can be seen in [4]. Almost all of the studies, whether experimental or numerical, generally consider the spray behaviour from new injectors or injectors manufactured for research purposes. The research conducted by our group focusses on determining changes in the fuel spray evolution and how it degrades over time under normal on-road operation of production injectors. For the measurements done on injectors at different stages of their life cycle, expulsions of macroscopic fuel droplets and ligaments were observed directly *after* the end of injection. Similar observations were investigated earlier by other research groups [5–8], and the impact of the number of orifices on these expulsions was recently studied in [9]. Although these post-injection expulsions represent only a very small amount of fuel mass compared to the total fuel mass injected during a typical injection event, their sizes are larger compared to atomized droplets from the main injection which leads to sub-optimal burning conditions that increases the engine-out soot. Earlier research by Musculus et al. [10] has shown that sub-optimal mixture compositions can occur near the nozzle at the end of injection, and this

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can lead to an increase in unburned hydrocarbon engine-out emissions. In contrast to the current investigation, the research conducted in [10] focussed on low-temperature-combustion operation, and considered overly-lean mixture composition near the nozzle as a prime cause for UBHC.

In the present investigation the behaviour of post-injection expulsions from production injectors, and the impact of injector age (mileage) on these expulsions, have been studied. By looking subsequently at the combustion characteristics of droplets and ligaments, it becomes apparent that these post-injection expulsions can contribute to additional engine-out soot and UBHC emissions. A similar investigation on a smaller subset of injectors have been conducted in a non-reactive environment by the authors at an earlier stage, and this has been reported at the IMechE *Internal Combustion Engines* Conference [11]. The results presented here however treat a larger dataset along with the incorporation of combustion characteristics of post-injection expulsions as speculated in our earlier publication [11].

2. Experimental conditions

The measurements in this investigation were conducted in a constant volume chamber (CVC) under varying conditions to study different aspects of a fuel spray injection event. The main part of the experiment was conducted in a non-reactive, inert, low-temperature environment, to study droplet and ligament expulsions when there is no interference from combustion or evaporation. A subsequent study was conducted in a high-temperature engine-like environment to investigate expulsions under reactive conditions. Combustion of the main fuel injection event led to slight optical degradation of the expulsions, but combustion of ligaments and droplets after the main injection remained clearly visible. Based on our earlier experience with high-power LEDs in combination with CMOS-based high speed cameras [12], a front-lit configuration incorporating a green high-power LED, synchronized with a high speed camera and fuel injection equipment was applied. Fuel expulsions were recorded after the end of the main fuel injection event: Up to 0.7 ms *a*EOI under non-reactive conditions, and up to 25 ms *a*EOI under reactive conditions. In the subsequent sections the ambient conditions, injectors and injection conditions, and the recording conditions are treated in more detail. Table 1 provides a quick overview of the main experimental parameters, Fig. 1 provides a schematic of the set-up as applied in this research.

Table 1
Overview of the experimental parameters applied in this investigation.

Parameter	Setting
Injectors	6-Orifice nozzle, common-rail, solenoid actuated
Conditions	New(3), 30 k-mile(4), 63 k-mile(4), 92 k-mile(3)
Injection pressure	50.0 MPa (reactive), 80.0 MPa (non-reactive)
Duration	1.5 ms
Non-reactive ambient medium	Gaseous N_2, >99% purity
Pressure	3.30 MPa (±0.01)
Temperature	112 °C–118 °C
Image scale	77 µm/px
Image dimensions	39 × 39 mm^2, 512 × 512 px^2
Reactive, high *P-T* medium	Products of acetylene pre-combustion
Composition	approx. 11:77:8:4 O_2, N_2, CO_2, H_2O
Pressure	2.55 MPa (±0.04)
Temperature	930 K (±30)
Image scale	130 µm/px
Image dimensions	67 × 67 mm^2, 512 × 512 px^2
Recording frame rate	45 kfps
Frame time	22.2 µs
Illumination time	1.25 µs
LED illumination wavelength	521 nm
FWHM	40 nm
Duration	2.6 ms

2.1. Non-reactive ambient conditions

Inert, non-reactive measurements were made at 3.3 MPa back pressure in a medium of pure nitrogen, heated to a temperature of 112 °C–118 °C. By maintaining a low chamber temperature, rapid evaporation of expelled fuel droplets and ligaments was inhibited, which allowed us to image these expulsions over a prolonged time. By maintaining the system at a temperature above 110 °C, settling of diesel fuel on the windows post-injection was prevented, as any diesel film on the optical windows would degrade image quality of subsequent fuel injections. At a back pressure of 3.3 MPa the governing spray deceleration and breakup would be comparable to in-cylinder compression pressures of HSDI engines.

2.2. Reactive ambient conditions

Combustion measurements of post-injection expulsions were conducted at an ambient condition of 2.55 MPa at 900 K–960 K. The high temperature and pressure for the reactive conditions were achieved by pre-combustion of a lean acetylene mixture (volumetric air to acetylene ratio of 25:1) in the CVC at a starting pressure of 0.52 MPa and an approximate temperature of 320 K. Combustion of this lean mixture resulted in sufficient residual oxygen to ensure complete combustion of diesel fuel when subsequently injected into the CVC. The mixture composition of the ambient gas during diesel fuel injection, after pre-combustion, is provided in Table 1.

2.3. Injectors and injection conditions

The primary goal of this research was to investigate the degradation of diesel fuel spray characteristics resulting from normal on-road vehicle use. The injectors used in this investigation were acquired from vehicles that are operated on the UK roads. All of the used injectors were acquired from passenger cars, all same type, and were removed during standard maintenance at approximately 30, 60 and 90 thousand miles. The injectors were all still in working condition, and were solely removed to facilitate our research. The injectors were divided into four batches depending on the usage history:

- *New*: 3 new and unused injectors,
- *Set 1*: 4 injectors removed at 30,000 miles,

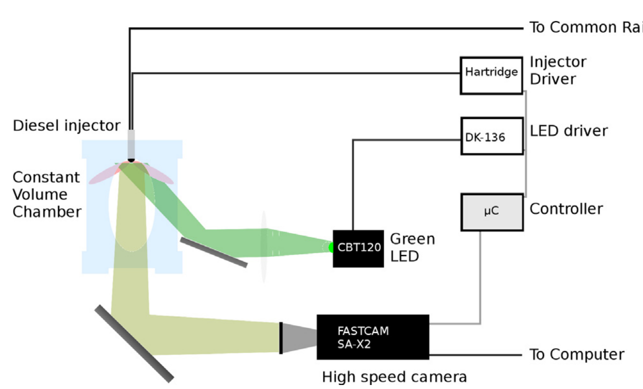

Fig. 1. Schematic of the experimental set-up as applied in this study.