Applied Energy 205 (2017) 391–398

Contents lists available at ScienceDirect

Applied Energy

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

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.

ARTICLE INFO

Keywords:
Diesel sprays
Used injectors
Deposits
Transients
Start of injection anomalies
Hole-to-hole spray variation

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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http://dx.doi.org/10.1016/j.apenergy.2017.07.092
Received 13 April 2017; Received in revised form 27 June 2017; Accepted 23 July 2017

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].

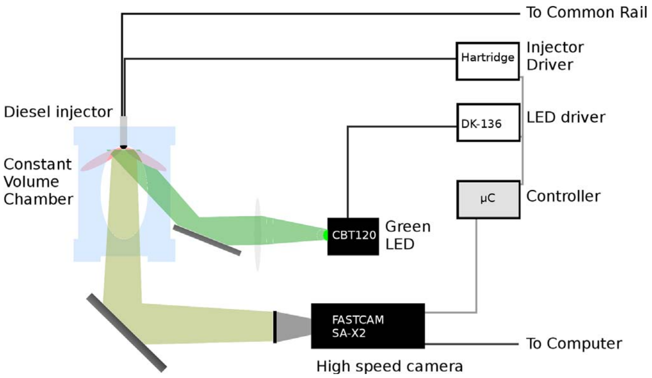

Fig. 1. Schematic of the experimental set-up as applied in this study.

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.

2.2. Injectors and injection conditions

Multi-hole, mini-sac, solenoid-actuated, light duty common rail diesel injectors were chosen for this investigation and they were acquired from servicing and maintenance companies. All injectors incorporated nozzles with identical part numbers, and came from similar passenger cars. The total batch of thirteen injectors consisted of four groups of injectors, all at different stages in their lifetime. One group consisted of two brand new injectors that had never been used inside an engine, and the sprays as recorded from these injectors were used as a base spray evolution benchmark, providing the ideal fuel spray pattern and evolution. The other three groups consisted of injectors taken from real world passenger cars from the UK commuter fleet, and were removed from vehicles that had done 30,000 miles (*set 1*), 63,000 miles (*set 2*) and 92,000 miles (*set 3*). The injectors from *set 1* and *2* each contained four injectors, *set 3* consisted of three injectors. It should be noted that although these injectors all clearly showed general signs of wear from normal usage, most notably the presence of deposits at the tip of the injector, all injectors were still in working condition and none of these injectors was in any way faulty (i.e. they were removed purely to facilitate our research). Combined SEM-EDX analysis of a nozzle from the *set 2* injector group showed deposits consisted predominantly of carbon and oxygen, and deposits were also present *inside* orifices. Fig. 2 shows two SEM images of a nozzle tip, providing (left) a general view on the injector tip deposit and (right) a magnified view of one orifice, clearly showing the presence of deposits inside the hole.

Injections were carried out using an EN590 compatible diesel fuel, and the common rail was maintained at a pressure of 80.0 MPa. The injector pressure used in this work was less than the current operating conditions, however our previous works on these injectors have shown that new injectors produced a good symmetrical spray penetration pattern even at rail pressures of 70.0 MPa. Injections lasted approximately 1.5 ms, of which only the first 0.5 ms was analysed, as this study focussed on the transients occurring at the early start of injection. The total injection duration was deliberately set this long to ensure any anomalies observed at the start of injection were not caused by a closing needle or other end-of-injection effects.

2.3. High speed imaging

Imaging of the evolving diesel fuel spray was done by front illumination with a high-power PhlatLight CBT-120-G green LED, driven at 36 A for the duration of 2.6 ms, synchronized with the fuel injection. This type of LED and the accompanying front-lit technique has been used by us in an earlier investigation [20] and proved to be more than sufficient for recording transients at the start of injection at high recording speeds. A Photron FASTCAM SA-X2 high speed camera recorded light backscattered off the atomized stage of the evolving fuel spray at a frame rate of 45 kfps, resolution of 512 × 512 px^2. The recorded area covered slightly more than 39 × 39 mm^2, providing an image scale of 77 µm/px. The camera recorded the nozzle by imaging the injector tip head-on. The sprays injected from the holes do not lie in a single plane, i.e. the cone angle is not 180°, and as a result there is a slight error in the orthogonality of the camera position with respect to the evolving fuel sprays. However, as the imaged area covers only 39 × 39 mm^2, the focal depth of the camera was sufficient to maintain a sharp image of the evolving fuel sprays. Needless to say, the non-orthogonality would require additional mathematical corrections of any quantitative results to correct for the slight plane mismatch, but these corrections are fairly straightforward and calculations showed the error incurred by ignoring the inclination would have led to a maximum systematic error up to 2.5%. As *all* nozzles and orifices were tilted by the same amount with respect to the recording plane, direct comparison of qualitative differences would be unaffected by this injection spray–recording plane inclination.

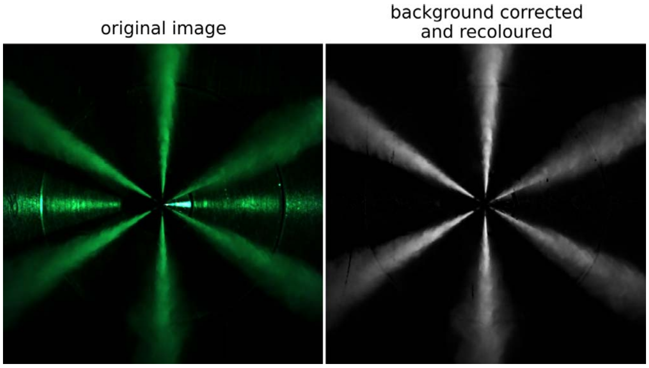

Fig. 3. Example of an imaged spray. Left provides the raw recording of a diesel injection event, 0.5 ms after the start of injection, as recorded from a new injector injecting at 80.0 MPa into a gaseous back pressure medium at 3.3 MPa, 115.2 °C. Right provides the same frame after optimization.

3. Measurements and observations

Application of the experimental set-up as treated in the previous section allowed the recording of several dozens of injection events from thirteen identical nozzles at different stages in their lifetimes. A typical spray structure observed with this system is provided in Fig. 3, where the left image provides a raw image as recorded in the CVC. The right image provides the same recorded image after background subtraction, gray scaling, and intensity re-normalization, which greatly improved the image quality. All subsequent images provided in this paper have undergone a comparable pre-analysis to enhance visibility of observed effects.

Used injectors investigated in this study provided a similar quasi-steady state fuel spray shape as the new injector shown in Fig. 3 after the initial transient start of injection, but showed very different early spray evolutions. Most notably, the hole-to-hole early spray evolution of several of the used injectors proved to be highly inconsistent and asymmetric, and the asymmetry observed at the early start of injection was found to be consistent from injection to injection. Fig. 4 shows the spray asymmetry at the early start of injection for four different injectors, one from each of the four injector mileage groups. Bottom row

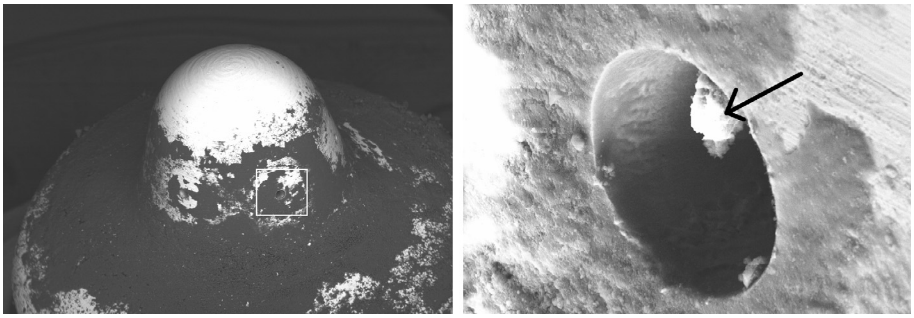

Fig. 2. Scanning Electron Microscopy images of a *set 2* injector nozzle. Left image provides a full view of the nozzle, where deposits are clearly visible as black patches. Right image provides a magnified view of the orifice indicated by the white square in the left image, and where a deposit (black arrow) is clearly visible inside the hole.

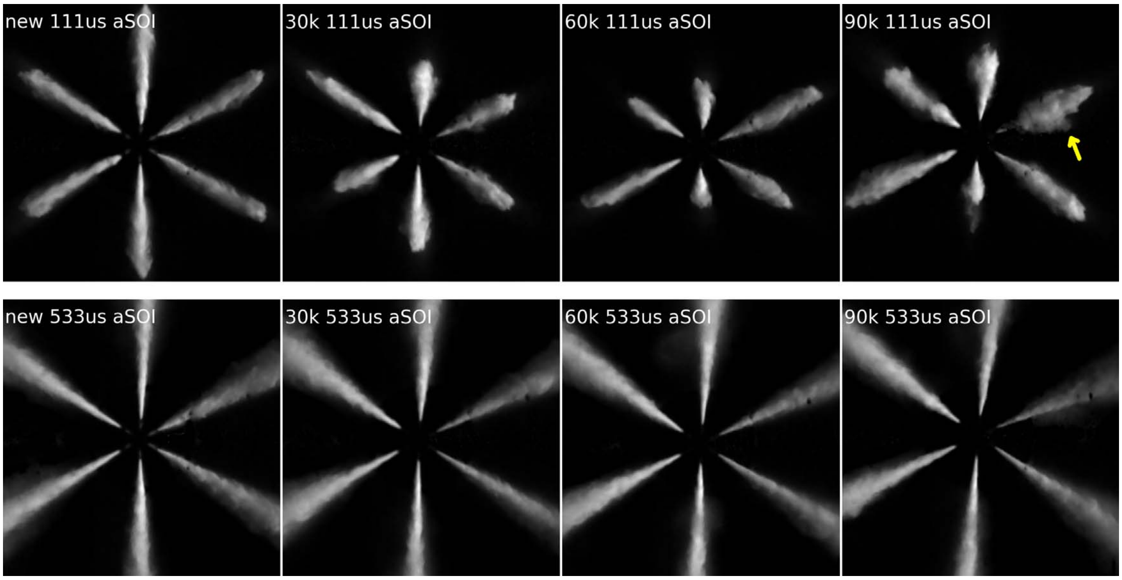

Fig. 4. Asymmetric evolution of the start of injection from four different injectors. Top row images were recorded at 111 µs after the start of injection, under similar injection pressure, back pressure and ambient temperature conditions. Bottom row provides the same recordings at 533 µs after the start of injection, showing a fully developed injecting spray. The worst-performing injectors have deliberately been selected to show these characteristics. Yellow arrow in top-right image indicates the presence of a transient off-axis anomaly. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

in Fig. 4 provides the nearly stable and repeatable spray shape from the same injectors in the quasi-steady state regime. Slight hole-to-hole spray variations were sometimes observed from a new injector, however for the new injectors hole-to-hole variations were much less severe than for the used injectors, and occurred less frequent.

The hole-to-hole spray asymmetry is visible in Fig. 4 as a reduced spray penetration from several orifices of the used injectors. The individually retarded spray is frequently accompanied by a widening of that spray. The retarded evolution might be due to a temporal reduction in axial momentum, and if the radial momentum component remains unaltered, this can lead to a radially expanding spray plume. This radial expansion is already visible for the *set 3* injector in Fig. 4 (yellow arrow), in addition Fig. 5 provides the evolution of such a radial transient, where for clarity a rather extreme case was hand-picked.

These anomalous radial expansions differ from the *mushroom head* or *spearhead* anomalies often observed to occur at the very early start of injection (see for example [2]). These *mushroom head* anomalies relate to residual fuel present in the tip of the hole at the start of injection and they constitute very small amounts of fuel, while the radially expanding transients observed in this article are clearly coupled to the reduced initial penetration rate. It is expected that the observed anomalies in this article are the result of a random intermittent change in the axial-to-radial momentum ratio. It is hypothesized, this change could partly be the result of internal fuel flow instabilities caused by internal surface modifications of the injector (i.e. deposits, cavitation damage, general wear, etc.). To illustrate the difference between the *mushroom head* SOI anomaly and the anomalies accompanying retarded spray evolutions, Fig. 6 provides zoomed in images of the very early start of injection. Here the presence of the *mushroom head* anomalies are visible for both a new and a used injector as a flattening of the spray head, although the effects are at the limit of the camera resolution. The used injector clearly shows an independent anomaly formed *after* the initial mushroom head had diffused.

4. Results

4.1. Asymmetric early evolution

The observed difference in the hole-to-hole variations of the early spray evolution when comparing new to used injectors were statistically analysed by averaging the spray penetrations from ten injections per injector for all thirteen injectors. After basic background subtraction, and corrections for specular reflections, the image was binarized with the help of a recording-specific threshold. Each individual binarized spray image was subsequently projected on the accompanying central spray axis, and the distance from the orifice to the spray tip along this axis was defined as the total spray penetration. In this manner the spray penetration was determined for every individual orifice of the injector and for every injection. The resulting spray penetrations plotted against time *a*SOI are shown in Fig. 7 and this enabled us to determine the occurrence and reproducibility of spray retardations. The slope of the resulting curve translates to (average) fuel spray tip

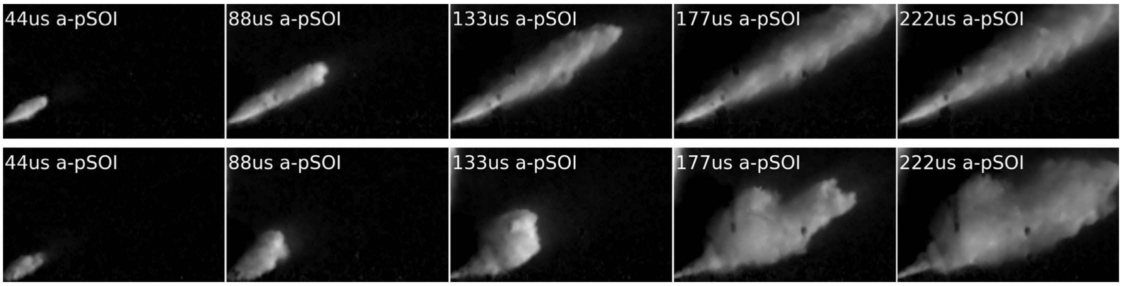

Fig. 5. Extreme example of a radial bulge often observed in combination with a low initial spray velocity. Top row provides the evolution from a new injector, bottom row a *Set 3* injector. For clarity, a zoomed in view of only one spray is provided. Times a-*p*SOI indicate time after the injection was *expected* to start.

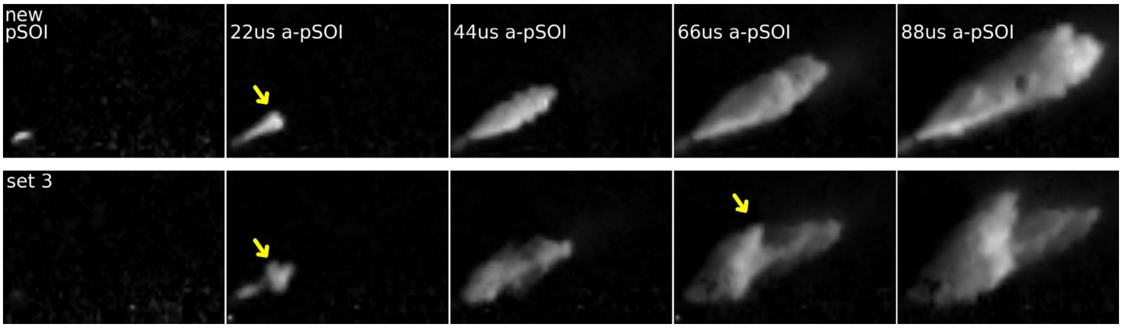

Fig. 6. Magnified view of the very early spray evolution from a *new* (top row) and *set 3* (bottom row) injector. Note how for both sprays the image in the second column shows a widening at the tip of the evolving spray, indicated by the arrow. The *set 3* injector clearly shows a subsequent independent radial anomaly forming shortly after the first transient, indicated by an arrow in the fourth image, bottom row.

velocity, and a reduction in slope therefore corresponds to a reduction in (initial) spray tip velocity. Trend lines with equal slopes but shifted with respect to each other correspond to retarded sprays that however still evolved with an equal spray velocity. The standard deviations are indicators for spray (anomaly) inconsistencies, for example a reduced slope with a low standard deviation indicates a slow spray tip evolution, where the inhibited spray evolution is however highly repeatable from injection to injection. When considering the first two graphs for the *new* injectors in Fig. 7, it becomes apparent that injector #1 produces six sprays which are essentially indistinguishable. Injector #2 shows that there is a slight discrepancy in spray penetration from different orifices, trend lines are shifted slightly with respect to each other, but the slope is nearly identical for all, indicating an equal fuel spray velocity from all orifices of the *new* injector #2. We are assuming that the slight variance observed in the #2 injector from the *new* set may be typical of batch to batch production variation.

The used injectors can be subdivided into injectors that are still behaving within the established parameters, and those deviating from design specifications. The gray region in the second to fourth row in Fig. 7 provides the spray penetration envelope of the *new #1* and *#2* injectors. The *set 1 #1* injector is shown to have more or less parallel trend lines with equal slopes, overlapping with the gray envelope for five out of six sprays. The sixth spray trend line (purple) drops just below the expected penetration in the later part of the graph. The behavior of this injector is almost as would be expected from a new diesel injector. Injector *set 2 #1* however shows that for one orifice (purple), the early start show a reduced slope when compared to the average slope range of the new injectors, which is indicative of a slow spray evolution as it falls outside the gray envelope. Later in time the spray rapidly accelerates and returns to the gray envelope, the spray comparable to a new injector again. In a similar fashion, *set 3 #1* shows two orifices having a strong slope change and an increased error bar, which is an indication that the sprays from these two orifices are retarded and additionally suffer strong variations from injection to injection. The retardation of two sprays for the *set 3 #1* injector additionally leads to an *increased* spray velocity for one of the remaining orifices (light blue trend), as the penetration increases above the gray envelope. Eventually the two retarded sprays undergo rapid acceleration and the spray

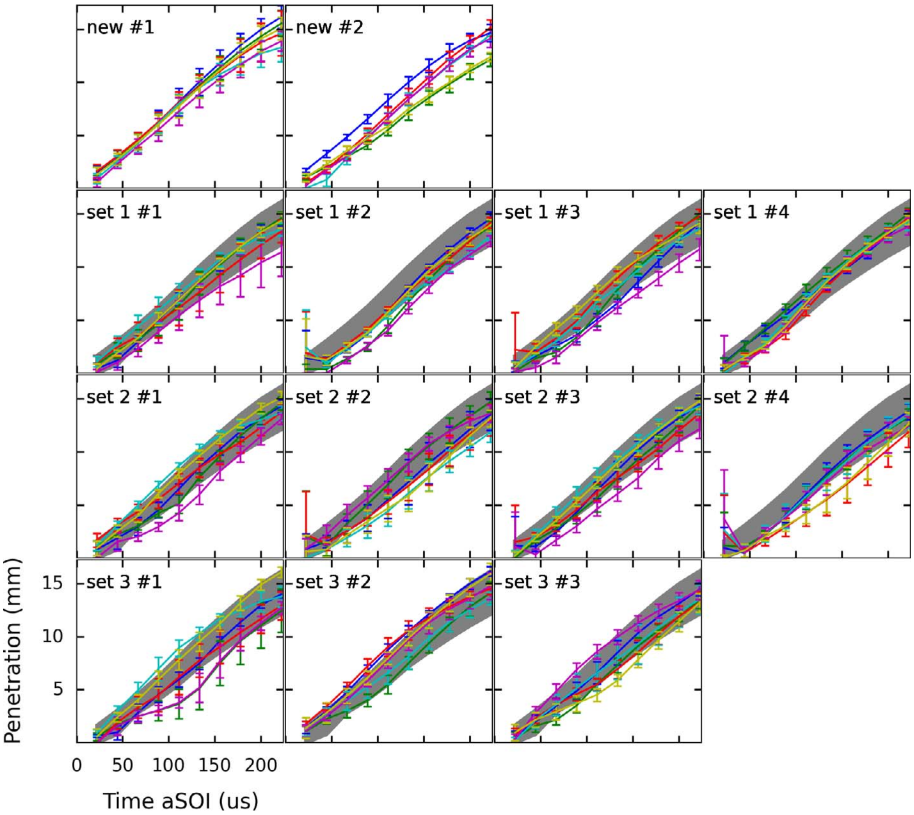

Fig. 7. Penetration curves for all injectors. Every graph shows the spray penetration plotted versus time for all six orifices of the injector under consideration. Gray background envelopes present in the *set 1* to *set 3* plots provide the encapsulated penetration graph of the two new injectors for reference purposes. Error bars indicate injection to injection penetration variations for a given orifice, while diverging trend lines indicate large hole-to-hole variations.

Table 2
Overview of observed penetration anomalies Fig. 7.

Injector		Observed anomaly
New	#1	Base reference for penetrations
	#2	Base reference. Note how the spread in penetrations is slightly larger than #1
Set 1	#1	One spray trend line (purple) shows slightly reduced penetration. Near-new behavior
	#2	Two orifices (purple, green trend line) produce retarded sprays in the early start. Injection as a whole seems retarded by nearly one frame (whole graph appears shifted to the right)
	#3	Relative broad spread of all penetrations indicates hole-to-hole variations, however only one orifice (purple trend line) shows a retarded evolution compared to the new injectors
	#4	Any hole-to-hole variation lies within the gray envelope, indicating this injector behaves indiscernible from a new injector
Set 2	#1	One orifice (purple trend line) produces a spray that initially evolves retarded w.r.t. a new injector but ‘catches up’ at 150 μs *a*SOI
	#2	Two orifices (light blue and yellow trend lines) show a reduced initial spray velocity, although not as severe as observed with *set 2 #1*
	#3	Similar to the #1 injector in the reduced initial penetration velocity (purple trend line), ‘catch up’ however occurs only at 200 μs *a*SOI
	#4	Two trend lines (yellow and red) indicate a reduced initial spray velocity for two orifices. In addition, the graph as a whole seems to be shifted to the right by one frame, indicating an overall retarded start of injection for this injector
Set 3	#1	Very strong reduction in initial spray velocity from two orifices, while simultaneously one orifice produces a spray (light blue trend line) with a higher initial penetration velocity than sprays from new injectors
	#2	Two orifices (red and blue trend lines) produce sprays which initially evolve faster than new injectors. Both red and blue trend lines lie *above* the gray background envelope up until roughly 170 μs *a*SOI
	#3	Large spread in initial spray tip penetrations. One trend line (purple) indicates a penetration rate slightly higher than for a new injector, while another (yellow trend line) simultaneously suffers a reduced penetration rate

penetrations ‘catch up’ with the sprays from the other orifices, as can be observed through a sudden increase in the slope for the bottom two trend lines. The different transient spray evolution patterns, and a short overview of all the observed anomalies of Fig. 7 are summarised in Table 2. Additional graphs providing the non-averaged penetration data from individual orifices of injectors *new #1*, *set 1 #1*, *set 2 #4* and *set 3 #1* are provided as supplementary information.

Additional qualitative understanding of the anomalies of fuel sprays from the used injectors was attained by comparing their spray penetrations against the new injectors at fixed times *a*SOI. Treating the average spray penetrations from the new injectors, averaged over all sprays from all orifices and all injections, as the average *expected* spray length, all observed spray penetrations from used injectors can be divided into *consistent* or *deviating* spray penetrations by comparing their penetrations with respect to new injectors. Applying a significance level of $\alpha = 0.05$, i.e. by considering a difference in penetration between new and used injectors of more than 2 standard deviations to be significantly deviating, a histogram of relative occurrence of *deviating* spray penetrations has been made. Fig. 8 provides the stated histogram, where for three different time instances *a*SOI the fraction of significantly deviating spray penetrations is plotted for every injector group. Two aspects are apparent when considering the histograms in Fig. 8:

- *Retarding and slow-evolving spray behavior is a temporal effect.* For 9 out of 11 *Set 1* – *Set 3* injectors, a significantly reduced fuel spray penetration was observed at the start of injection. For some injectors up to 40% of all sprays showed a reduced early spray penetration, with spray penetrations reduced by more than 2 standard deviations when compared to sprays from new injectors. After approximately 200 μs nearly all of the retarded sprays had accelerated and caught up, as shown in the bottom row of Fig. 4. Only two out of thirteen injectors (*Set 1 #1* and *Set 2 #4*) incidentally produced spray penetrations which deviated more than 2 standard deviations relative to a new injector 200 μs *a*SOI.
- *Different injectors within a single engine can show large differences with respect to penetration retardation.* Injector *Set 3 #2* provides no significant retardation when applying the 2 standard deviation threshold, while the other injectors from the same *Set 3* group show strong penetration deviations compared to a new injector. Taking a closer look at *Set 3 #2* in Fig. 7, it becomes apparent that sprays from different holes do structurally produce different penetrations and penetration rates, however the differences are not significant when considering the total variation observed within the portrayed gray envelope of new injectors. Similar observations can be seen for *Set 1* and *Set 2* injectors.

4.2. Transient radial expansion

As briefly described in Section 3, reduced spray tip velocities and penetrations were nearly always accompanied by radially expanding anomalies. Although the reduction in initial spray tip velocity was fairly reproducible from injection to injection, the transient radial evolution of

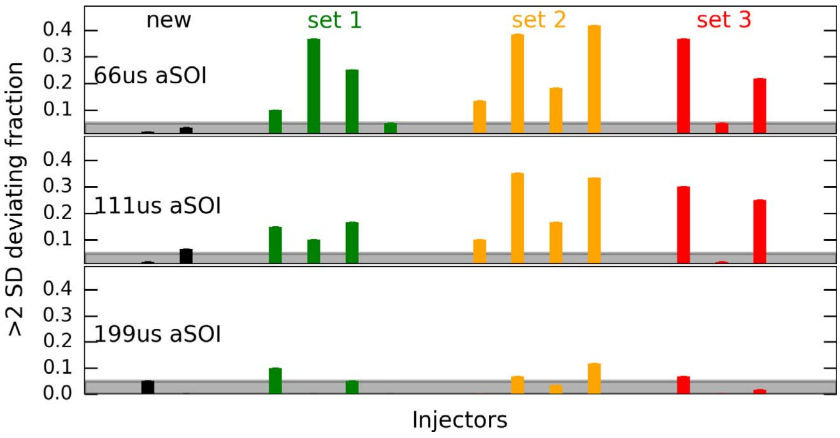

Fig. 8. Relative occurrence of significantly deviating spray penetrations for sprays originating from used injectors, with respect to new injectors. Every bar represents, for one injector, the fraction of sprays that significantly differ in penetration compared to both new injectors. Significance levels are determined by application of an $\alpha = 0.05$ threshold. Light gray band provides a minimum fraction threshold above which occurrences can be considered to be significant, as by definition 5% of the measurements are expected to differ more than 2 SDs.

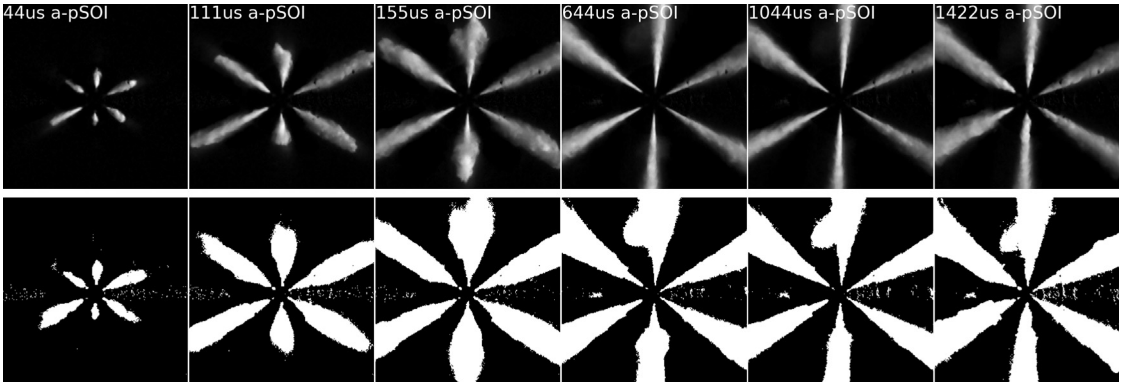

Fig. 9. Spray evolution from a used injector, showing the persistence of the off-axis atomized stage long after the transient period should have passed. Top row provides a color-optimized view of the fuel spray, bottom row provides same spray images, binarized with the application of a 2× noise level threshold. Images corresponds to a $19 \times 19\,\text{mm}^2$ area.

plumes as shown in Fig. 5 and their morphologies were not constant from injection to injection, making quantitative analysis impractical. As can be seen in Fig. 9, transient expansions are not necessarily symmetric around the fuel spray cone, which might explain why radially expanding transients show large variations from injection to injection. As the sprays are imaged in a 2D plane, any radial expansions occurring in the imaging plane will be recorded at its maximum diameter whilst any radial expansion occurring at an angle to the imaging plane will show a reduced diameter. Any transient radial plume variations occurring normal to the imaging plane will be invisible, as there is no 3D reconstruction possible from the recorded images. As the radially expanding transients cannot be assumed to be symmetric around the fuel spray cone, quantitative results lie beyond the scope of this article as it would require several unverifiable assumptions. Time-tracing of the individually observed radial expansion of spray plumes did provide an interesting qualitative result. The operating conditions of the CVC applied in this research were deliberately chosen to minimize evaporation of the injected fuel spray. Some evaporation did however occur, which, combined with diffusion of off-axis transients, led to an apparent disappearing of the radially evolved transient spray plume. Application of noise-level threshold binarization allowed us to discern the radial evolution of the atomized spray cloud at its spatial location up to the end of injection. Fig. 9 provides image sets from a *Set 2* injector, showing the evolution of the fuel spray, accompanied with a low-threshold binarized version of the same spray images. Note how the radial expanding anomaly seems to have disappeared at 644 µs *a*SOI in the top image row, but with the application of a suitable threshold it remains discernible up to 1.422 ms *a*SOI, just before the end of injection. Nearly all used injectors produced similar radial expanding transients, although in general the largest transients were observed at the higher mileage injectors. The effect of these large fuel pockets present near the nozzle on the ignition and combustion characteristics has not been studied in the present investigation.

5. Discussion

Although a clear alteration of the very early spray evolution has been observed when studying used production injectors, the cause of the observed radial expansions or reduced initial spray tip velocity is yet unclear. As stated in Section 3 the radial expansions observed at the start of injection are, as far as we can determine, *not* related to the *mushroom head* spray anomalies often observed when closely studying the very early start of injection. Although at the limit of the resolving capabilities of our camera, some recordings allowed clear discrimination between both types of radially expanding SOI anomalies. In all cases the retarded early spray evolution was compensated by a sudden acceleration of the spray tip from the same orifice. The retarded sprays often showed a broadening of the spray similar to, but much larger than, the very early *mushroom head*-typed radial expanding anomalies.

We expect the retarded spray evolutions, subsequent acceleration, and spray broadening to be the result of alterations in the internal flow pattern inside the injector. Changing the internal flow structure may lead to an intermittent fuel flow from the nozzle, and different orifices may temporarily produce different penetration rates as the effective pressure fluctuates inconsistently during the initial phase of injection. The clearly observed anomalies when injecting with used injectors are (nearly) invisible when measuring new injectors. The internal flow alteration is then expected to be the result of changed internal injector geometries, where causes for changes must be sought in the daily use of such injectors, and will include: deposit formation in/on the nozzle, cavitation damage in the orifices, general wear of mechanical parts, and perhaps lubricity issues or scaling upstream of the nozzle leading to an unbalanced needle lift. Investigation into the actual mechanism that causes the observed anomalies is beyond the scope of this investigation. The hole-to-hole variations observed in spray penetration during the early start of injection should be of concern for injection systems that employ pilot injections, as these hole-to-hole variations may occur for every pilot injection from a used injector.

6. Conclusion

Thirteen injectors, all incorporating nozzles with identical part numbers, have been studied to determine changes in the injected fuel spray pattern as a result of normal on-road use of these injectors. By close investigation of the spray penetration at the early start of injection it has been shown that used injectors can produce high hole-to-hole variations. In the quasi-steady state regime the fuel sprays from used injectors are comparable to those from new injectors, however the highly asymmetric start of injection will lead to a reduced early spray penetration, roughly up to 200 µs *a*SOI. Reduced spray penetrations from individual orifices nearly always coincided with the occurrence of radial expanding transients, and off-axis fuel pockets resulting from these transients remain nearly stationary close to the nozzle tip.

Usage (mileage) seems to be a fair qualitative indicator of the expected injection quality with respect to hole-to-hole uniformity of the early spray evolution, although injector to injector variations at a fixed mileage can be considerable.

Acknowledgements

This work has been sponsored by SHELL Global Solutions (UK). We would like to thank Ian Moore, SHELL Global Solutions (UK), for procurement of the used injectors studied in this investigation. We also would like to thank Frans During, SHELL Technology Centre Amsterdam (NL), for providing the SEM images and EDX analysis of the used nozzle.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apenergy.2017.07.092.

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