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Analysis of PDA measurements on a double injection GDI spray

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Abstract

A N-heptane spray from a GDI multi-hole injector operated in ambient air at fixed conditions and with double injection commands is studied with different experimental techniques to better understand the spray behaviors, focusing the analysis on the effect of different dwell times between the two pulses. Results from spray photographic analysis, fuel injected quantity, droplet velocity and sizing by Phase Doppler Anemometry are presented and compared. The peculiarities and usefulness of a complementary application of the different techniques is illustrated. The two spray pulses have the same time length, so that the first spray evolves in a nearly quiescent and clean ambient, while the second, nominally identical to the first one, evolves in its trailing edge. The direct comparison allows an immediate perception of the differences among the two sprays, at the different dwell times, where the shorter tested, 160 microseconds, was chosen as the one that shows the first appreciable effect with at least one of the used techniques; the differences are clearly evident in the PDA results, sufficiently visible from the injection rate, not appreciable in the imaging at short distance. The effect of the longer dwell times becomes more evident and is illustrated.

Keywords

GDI, Spray, Double Injection, PDA, droplet sizing

Introduction

The process of fuel injection is crucial for the mixture preparation in automotive engines, and the use of fuel direct injection is considered also in gasoline engine an efficient way to attain better performances in terms of energy efficiency and pollution reduction. The experimental effort to characterize the GDI engine with its component has been huge in the last decades. The multi-hole injectors geometry and the electronic control allow to use a large number of parameters to attain the desired results, among which injector hole sizes and spray pattern, fuel pressure, injection timing and duration, where also split or multiple injections can be used [3, 8]. Different experimental techniques are continuously improved and used to characterize GDI fuel sprays, both with the aim of understanding the effect of the controlling parameters, and to provide accurate data for modeling and CFD tune-up and calibration. Being split injections and GDI spray droplet sizing [5] widely studied since years, the present work accurately reports a parametric study focused on the effect of the dwell time on the spray droplet velocity and size and generally on the second spray behavior.

Experimental set-up

The used injector is a standard production injector, (part number VW 03C 906 036N produced by Magneti Marelli) with static flow rate of 13 mm^3/ms (N-heptane at 100bar), used in GDI engines with relatively small cylinder capacity. Its spray pattern presents five plumes, one of which is nearly axially oriented, and at the same time widely accessible from its sides, thus resulting favorable for the PDA measurements nearly like with a single hole injector. The same injector sample was used for all the tests, although different samples were available. N-heptane was chosen as model fuel, widely used for better result reproducibility, although it is not really representative of real gasoline behavior due to its higher boiling point [2]. The experiment were conducted in two different laboratories with different experimental set-ups; slight differences exist among the two fuel pressurizing systems, in the geometries of the rail volumes, and in the injector power stage, with current timing and intensity that may differ slightly, with a difference in the rise-up of the current peak evaluated as 20-30 microseconds.

Injection Rate set-up

The tested injector was characterized in terms of injection rate profile by means of the proprietary instrument 'UniPg Injection Analyzer'. The fuel injected into the closed measuring chamber causes a pressure increment. By time-deriving the chamber pressure signal, the injection rate time-history can be obtained according to the Zeuch method [7]. After each actuation cycle, a fast electro-valve is opened, discharging the fuel and restoring the original base pressure before the next injection cycle starts. As the fluid bulk modulus is significantly influenced by

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both temperature and pressure, the instrument is able to continuously calibrate by measuring the mean injected mass and the fuel density by means of a Coriolis mass flow meter (Siemens Sitrans CF 2100) placed downstream the measuring chamber. After a proper thermal stabilization in each operating condition, the acquisition procedure is repeated for some hundreds of consecutive injection cycles in order to allow a statistically significant analysis of the process mean characteristics and of its shot-to-shot dispersion. Further details about this instrument can be found in [4].

Photographic set-up

The spray is directed with the injector axis (Z_{INJ}) oriented vertically downward, with the spray pattern symmetry plane corresponding to the electric connector, marked as X_{INJ} axis and used as rotation reference. The injector is mounted in a rotating flange on the top of the closed bomb detailed in [2], kept with open windows (90 mm diameter) to have a confinement but not a pressurization, and a continuous air renewal. A schlieren system operated without the knife edge is used to obtain back-light photographies without any perspective distortion. A PCO Sensicam Fast shutter is used to capture single images of the spray in the XZ_{INJ} and YZ_{INJ} planes. The image resolution is set at 10 pixel/mm, the exposure about 1 microsecond.

PDA set-up

A Dantec BSA P80 Phase Doppler Anemometer is used, equipped with a 310 mm focal length lens on the transmitter, and a 500 mm lens on the receiver oriented at 70° side scattering angle. Axial velocity is set in the range -10 to 130 m/s, with the positive direction directed downward in the laboratory, the droplet maximum diameter is set at 80 microns.

Experimental conditions

The experimental conditions are fixed, with only the command pulse shape used as a parameter, with single pulse and double pulse injections with variable dwell time as reported in the following Figure 1.

Experimental parameter	value
Fuel Pressure	100 bar
Fuel and injector temperature	30°C
Air conditions	ambient
Logic pulse, single injection	1 ms
Logic pulse, double pulses	1+1 ms
Dwell time for double pulses (chart on the left)	160, 200, 300, 500, 1000 μs

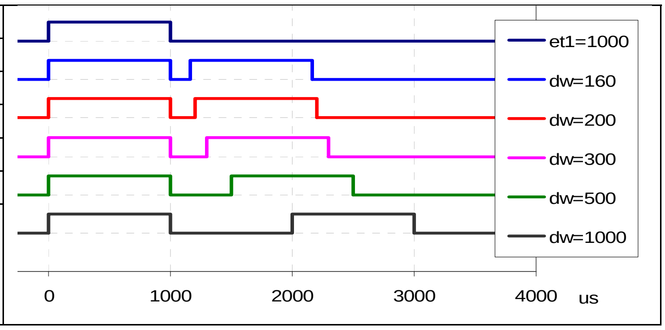

Figure 1. Experimental parameter values and pulse time diagram for the different dwell times

Injection rate results

The injection rate, reported in figure 2, reflects quite directly the injection command. The initial negative injection rate values before the injection hydraulic start may be speculated to reflect the inward needle opening, that results as a minimum suction of fuel from the instrument measurement volume as discussed in [6].

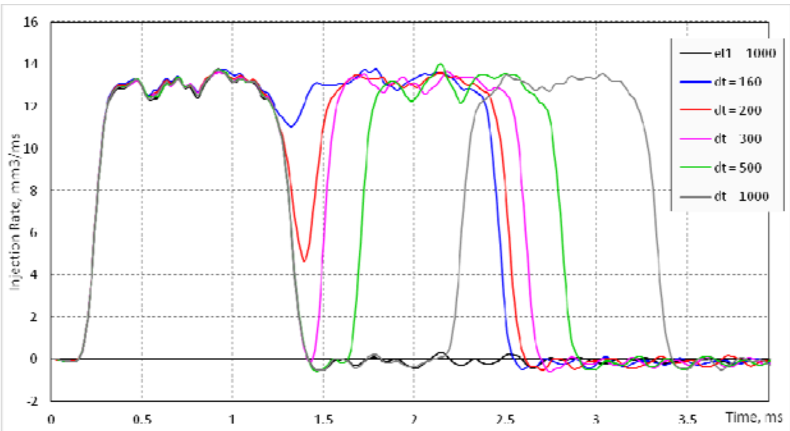

Figure 2. Injection rate results (mg/ms), for the different dwell times (μs)

The first increase quantifies the injector opening delay, in the same way the decrease after the closing command reflects the closing delay. Both delays depend on the constructive and operative parameters of the injector; in the

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present case the closing delay is longer than the opening one thus causing the fuel injection period being longer than the logic pulse. The duration of both opening and closing slope is in the order of 100÷150 μs. The quasi steady injection rate value is about 13 mm^3/ms, with slight oscillations due to typical hydraulic wave effects.
In this set-up the minimum dwell time tested, 160μs, was the one that showed a visible decrease of the injection rate, about 10%, sufficient to be distinguished from the hydraulic pulsations. It should be mentioned again that the injection rate set-up uses a different electronic power stage, and a possible difference in the order of few microseconds compared to the optic bench may be reasonable. For shorter dwell times the injector inertias, electrical and mechanical, merges the two logical pulses in a unique continuous injection event.

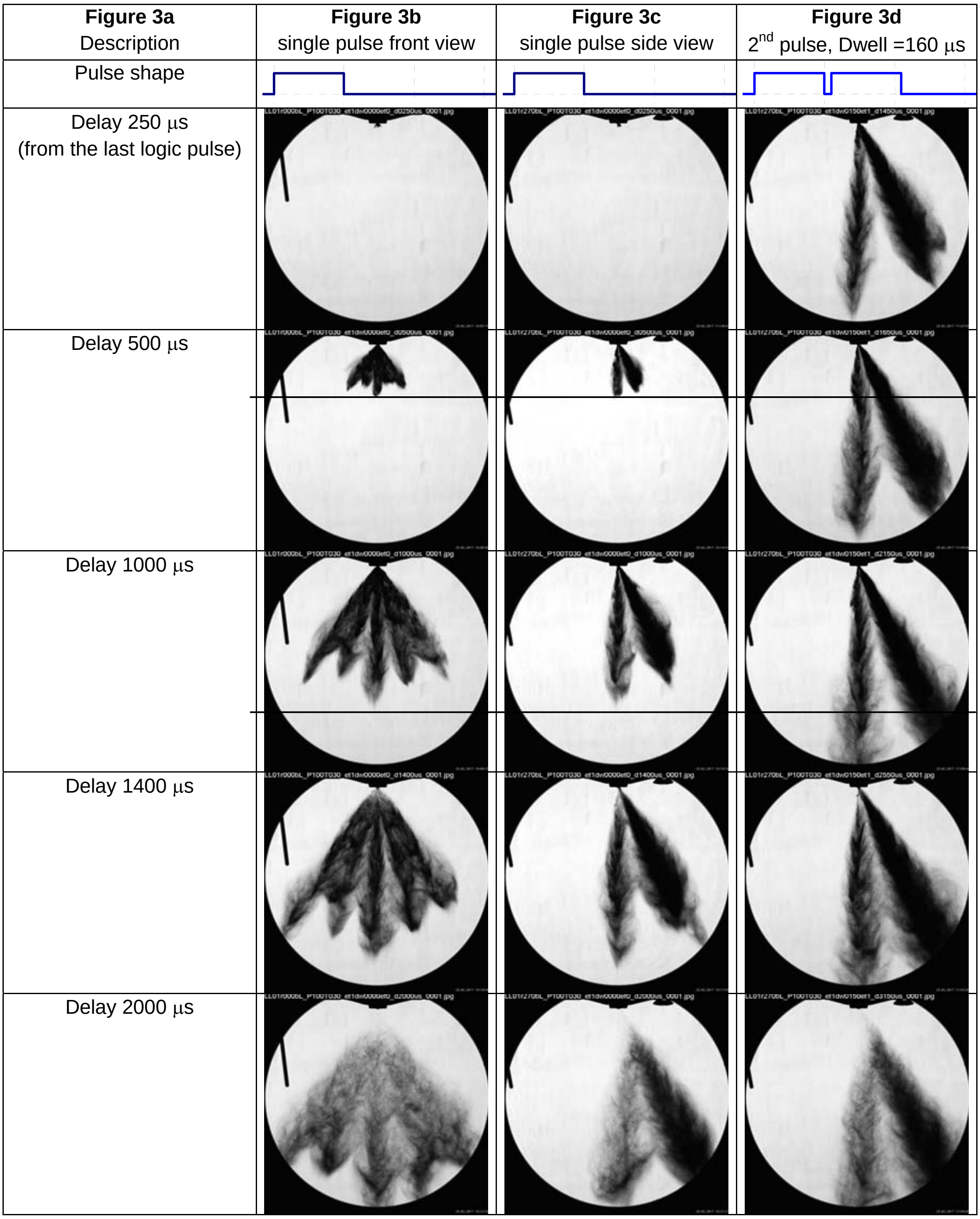

Figure 3. Evolution of the spray with the different pulse shapes

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With dwell time of 200 μs the injection rate is reduced by 30% before increasing again due to the second pulse command. With dwell time of 300 μs the closing is complete before the second pulse, whose trace reproduces quite similarly the trace of the first one. Longer dwell times confirm that, for what concerns the injected quantity, the two pulses look mostly independent; this coherence in terms of injection rate between the first and the second pulses is due to both the relatively long dwell time (pre-magnetization effects are negligible) and the rather long energizing time that ensures the complete needle lify displacement (no ballistic behavior).

Photographic results

Figure 3 presents a short extract of the photographic analysis showing a short history of the spray evolution.

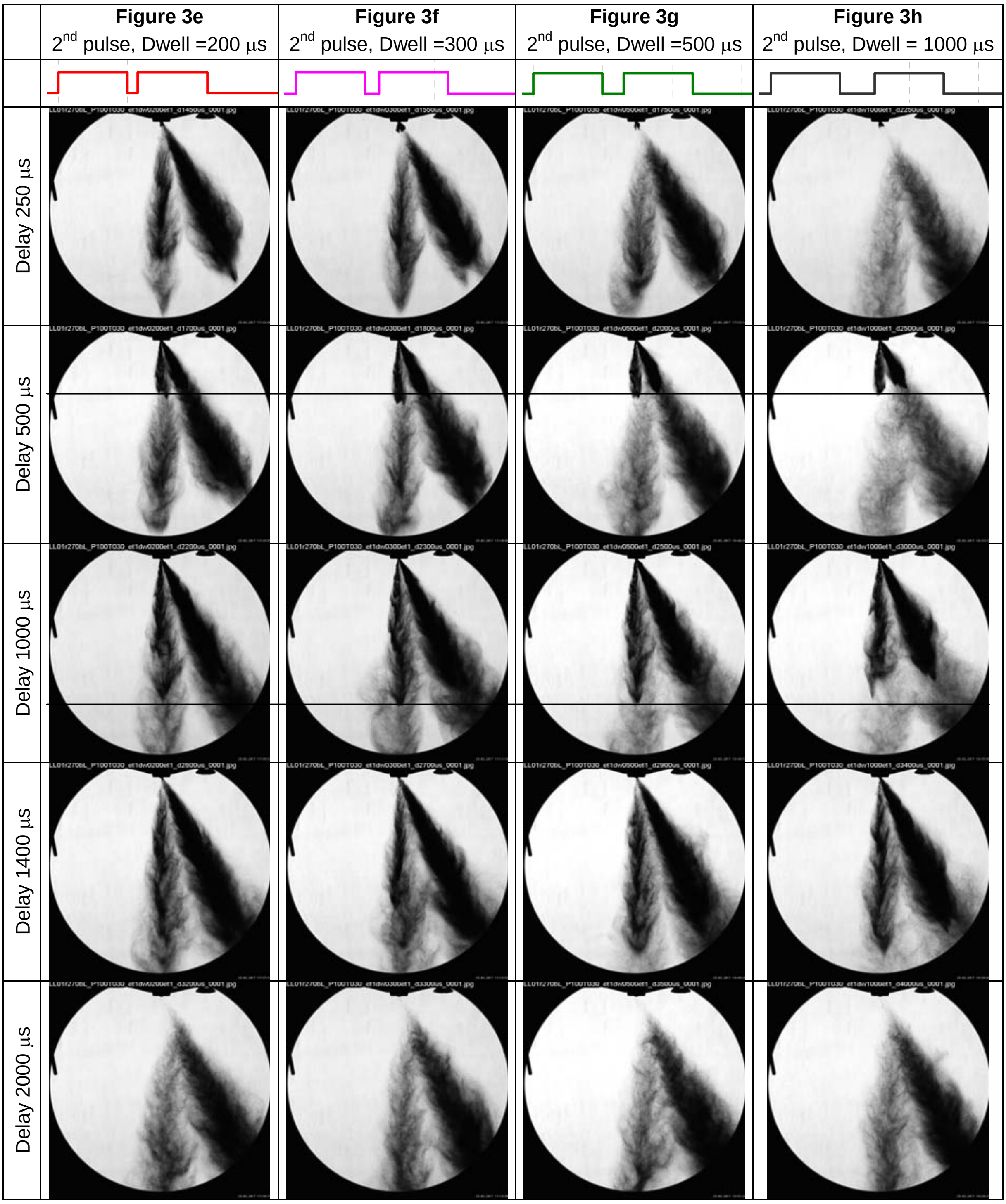

Figure 3. Continuation

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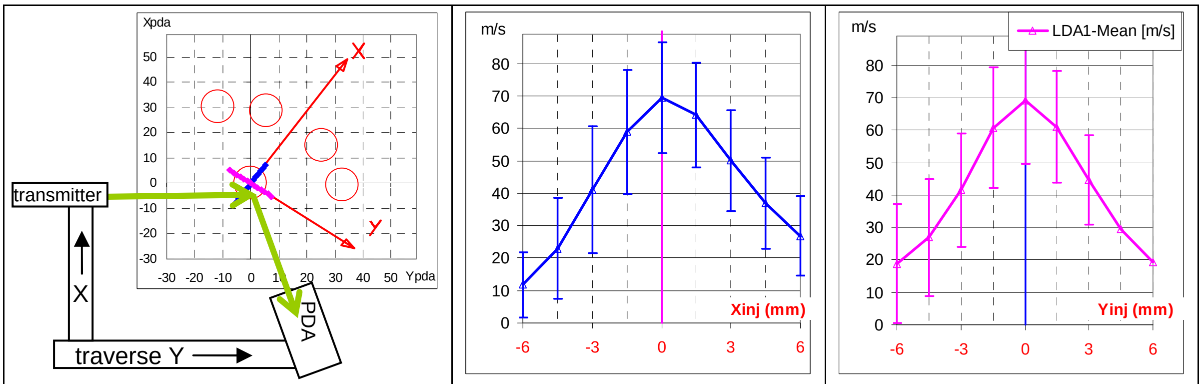
The delay of each image is indicated starting from the beginning of the last logic injection pulse, so that the differences can be more easily perceived.
With a single pulse spray, that is the same as the first of a double pulse injection, the spray evolves in undisturbed air, starts to be visible 250μs after the trigger due to the opening delay, and the needle closure is clearly visible at 1400μs, i.e. 400μs after the logic command end. A shorter closing delay can be supposed, but not clearly observed with photography.
For the dwell time of 160 μs, the shortest tested, in the images of figure 3d it is difficult to perceive a clear distinction between the two pulses, that becomes more and more visible as the dwell time becomes longer. A reference line is added over the Figure 3 to help in locating the spray tip at 500 and 1000 μs delays.

PDA centering
The PDA traversing system is installed with its origin and Z_{PDA} axis coinciding with the injector ones, used as rotation axis to optimize the injector position for easier experimental configuration and access to the investigated plume. The PDA transmitting optical axis is directed as the Y_{PDA} traverse axis of Figure 4, where different colors are used to easily identify the different PDA and Spray reference systems. The two systems are centered with accuracy better than 0.2x0.4x0.2 mm, along the $(X,Y,Z)_{PDA}$ reference directions illustrated in Figure 4a.
For the PDA measurements, after the correct centering of the two reference systems, the PDA measurement volume is centered on the selected spray plume at the axial position Z=45. Measurements are performed along a cross pattern composed by 9+9 positions spaced by 1.5 mm along the injector XY_{INJ} reference system. For this purpose a longer injection is used, 2 ms, to measure the average velocity during the quasi-steady injection period, and 200 injections are recorded at each position for good statistics. The results reported in figure 4 show the good centering of the plume, that is symmetric along its Y_{INJ} axis, and slightly asymmetric in its X_{INJ} direction due to the suction effect of the other four plumes. Such effect was clearly visible in the photos, with the central plum attracted by the other ones after the needle closure. These results are quickly processed on, so are not bias corrected and may differ from the following results.



a) The spray XY axes, the nominal pattern at Z=45mm, and the investigated plume with the PDA optics position, the XY_{PDA} axes and the measurement positions pattern	b) The quasi-steady axial velocity profile (average ±σ) along the X_{INJ} axis, at Z_{PDA}=Z_{INJ}=45mm. Note the slight asymmetry.	c) The quasi-steady axial velocity profile (average ±σ) along the Y_{INJ} axis at Z_{PDA}=Z_{INJ}=45mm

Figure 4. PDA cantering on the spray plume. Colours are used to ease the identification of the different axes. These averages are not Bias .

PDA results
To study the effect of the dwell time, PDA data are recorded on the central position of the plume found in figure 4. For each condition, 1000 injections are recorded to improve the statistics. Results are averaged in time windows of 100 μs duration, centered around their nominal value, and reported in figure 5. For each time window, the typical average results for droplet population are computed: average velocity, diameters D_{10} D_{20} D_{30} D_{32}, and the number of counted droplets, that normally is more than 10000 in each time window. The PDA bias is corrected for by weighting the droplet data in function of their diameter with an empirical function. Together with the count plots, in Figure 5c is reported the real timing of the pulse logic command. In the column 4b, the pulse is displayed shifted in time until the first droplets are measured, to ease the understanding of the spray time evolution and direct comparison of results.
<u>**The single injection**</u>

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The single pulse injection, that is the same as the first of a sequence, allows a comparison also to the second pulse also after the needle closure, so that the two trailing edges can be compared.
Average velocity and diameters are compared using as reference the quasi steady values. Different phases can be distinguished

First fast single droplets

The graphs show quite often few large and fast droplets at the beginning of the injection, with velocity 10% higher and diameters 50% higher than in the quasi steady period. It should be noted that the graphs are the accumulation of 1000 injections, while those fast droplets are only few tens, meaning that in cycle resolved results, they would appear only randomly once every many tens of injections, while the following time windows collect many thousands of droplets.
The faster droplets presence can be supposed as the effect of an aerodynamic selection at the spray front, and in the average results they may show up or not, hidden by the more numerous slower droplets, depending also on the chosen time window positions. Their relative weight is limited: even with 50% larger diameter, that is 4 times the individual volume and mass, they represent less than 0.5% in number, so 2% of the mass of one of the following windows, but in a graph the two groups are represented each by one symbol, being perceived at first sight as having the same relative importance.

Initial slow droplets

The following two time windows show droplets that, compared to the quasi steady ones, are initially 15% slower (50 vs. 58 m/s), and 40% larger (D_{30} 14 vs. 10 μm), and then converging to the steady values. The number of detected droplets quickly reaches the maximum value, 5 to 10 or more thousands per window.

Quasi steady period

Velocity, size and number of detected droplets per time window keep quite stable, with values around 55-57 m/s, diameters ranging from D_{10}= 9 μm to D_{30}= 15 μm, and 10 to 15 thousands counts per window. Some small oscillation are repetitive in all the tested cases.

Trailing edge

The needle closing is followed by a fast but not sharp velocity decrease, with smaller dimensions, averaged diameters are roughly halved, while the number of detected droplets that decreases as the velocity, typical of the PDA technique that relies on the single counting of particles (when their volume concentration in the flow is constant, the detection rate is proportional to the flow velocity).

Far trail

For times after 3 ms, the velocity falls down below few meters per second, and only few and slightly larger droplets are left suspended in the air.

The second injection

The second injection is quite similar to the first one, except in its initial phase, where its tip merges the trailing edge previous pulse.
The first fast single droplets never show up, may be because statistically masked by the largest number of very slow droplets present in the ambient.

Initial slow droplets

In this phase the second injection shows quite different results. The rise up is much slower and requires more time, nearly 1 ms to, reach the same steady value of the first pulse. This behavior is a consequence of the merging and partial mixing with the slow trailing edge of the previous pulse, as visible in Figure 6, where the two population may still be distinguished The slow droplets suspended in the air, are only partially accelerated, while at the same time there is a lack of fastest droplets. The average result is a decrease of the mean velocity. The effect is less visible for very short dwell time, where the trailing edge has no time to slow down. The measured diameter do not show the initial large droplet, but it can not be argued if they do not exist, or if their presence is also masked in the average values by large quantity of suspended small droplets of the trailing edge.

Quasi steady period

It shows the same average values as the first pulse, it keeps just shorter in the present experiments, It should be noted that in the case of a short second pulse as often used in a real engine, the steady period would not be reached, as only the longer transient part would appear in the measurements.

Trailing edge

No clear evidence of any difference can be observed in this part.

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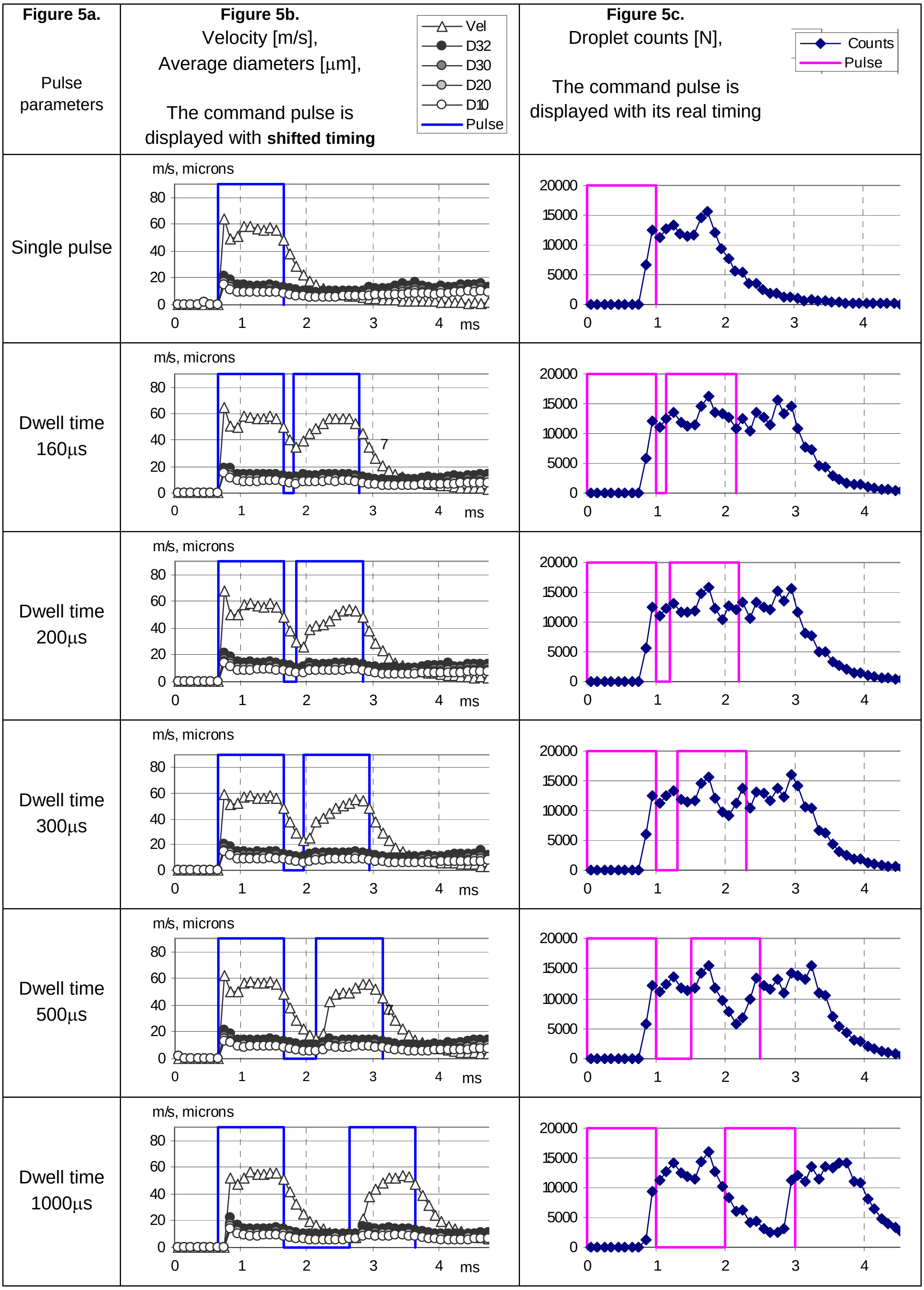

Figure 5. PDA average results

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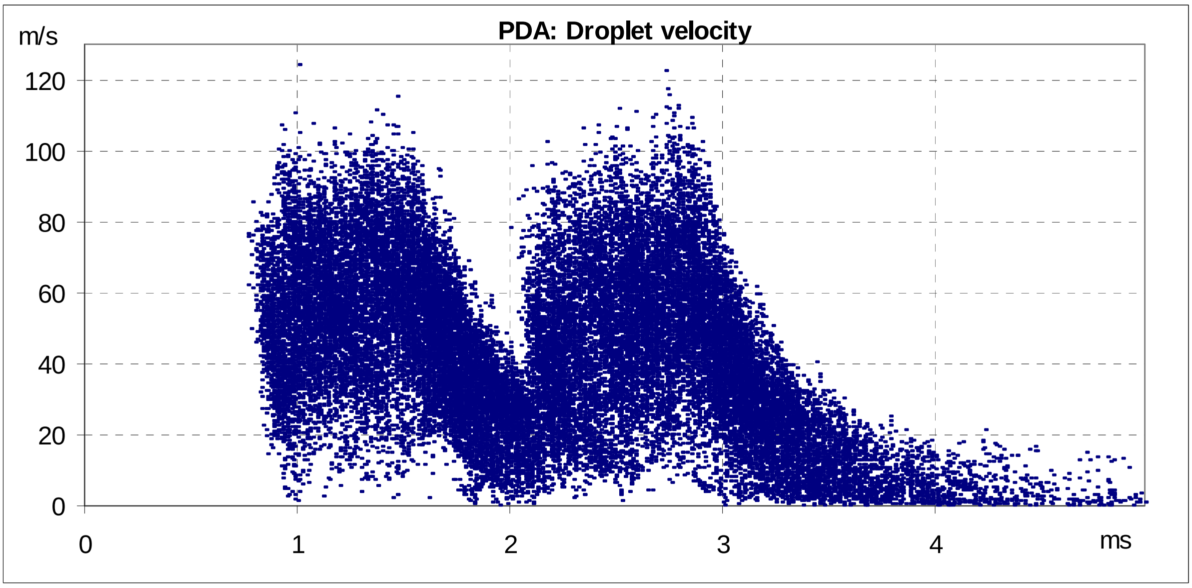

Figure 6. PDA results: droplet velocity for dwell time = 300 microseconds

Conclusions and perspective

The comparison of the three techniques offers complementary results.

The fuel rate results can detect in the fuel flow, minimal variations that are not shown by photos, but the information is limited the nozzle exit position, and can not give any further information on what may happen more downstream in the spray. Further, the hydraulic analysis is relevant to all the jets emerging from the nozzle. Photographic results offer a global view of the spray, thus also of the interaction and merging of the two pulses, but are blind in the most dense regions of the inside spray or in its denser wake, so for example can give precise estimate of the opening delay, but not of the closing delay or of the events for short dwell times. Laser Doppler results can gives many complete and time resolved information but in a single position; different positions may be investigated, but the process is extremely time consuming. The PDA can detect some effect for very short dwell times, but may become blind in regions that are optically very dense. The use of the three techniques is useful to build up a more detailed and comprehensive understanding of the spray evolution

Nomenclature

LDV	Laser Doppler Velocimetry
PDA	Phase Doppler anemometry
GDI	Gasoline Direct Injection

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