Experimental investigation on the spray behaviour for a hollow cone piezo injector with a multiple injection strategy

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Abstract

The traditional goal in engine development is to minimise the fuel consumption while maintaining or improving performance combined to lowering of the primary emissions [1]. One strategy to achieve this goal for spark ignition engines is gasoline direct injection. The injector technology has evolved rapidly and the recent introduction of the piezo hollow cone injector promises a very wide flexibility to cover many different engine requirements such as cold start, full load or stop and go driving. Due to its piezo activated needle, different needle lifts can be applied easily and with an extremely high reproducibility. This work demonstrates the results of the spray analysis for a piezo hollow cone injector operating with two different injection strategies which result in the same injected mass. One strategy works with a reduced lift and a long injection duration while the other is a multiple injection strategy consisting of a medium lift and five short, independent injections. To compare the sprays produced by the two strategies three optical techniques have been applied: Mie scattering, shadowgraphy and 2D PDA to characterise the liquid and vapour phases and droplet velocity and size distributions respectively. The different injection strategies have a substantial influence on the spray penetration, droplet velocity and the vapour phase distribution, while the droplet size is barely influenced. It is shown that the piezo hollow cone injector not only demonstrates that rate shaping is possible, but also that it has a spray shaping capability.

Introduction

In automotive engineering the fundamental goal is to reduce carbon dioxide emissions, while simultaneously keeping stable or even lowering the primary emissions such as PM, NOx or UHC. For Spark Ignition engines gasoline direct injection is, among other techniques, a powerful technology to achieve such goal. Regardless of whether a stratified or homogenous combustion, spark ignited or auto ignition concept is adopted, bringing the fuel directly into the cylinder offers a wide range of possibilities for NO_x and CO_2 reduction [2]. Different injector types have been demonstrated since the introduction of gasoline direct injection engines [3]. However, multi-hole injectors are beginning to show more wide spread application, but with increasing rail pressures there are issues to be addressed [3]. Another approach is the piezo activated, hollow cone injector. Due to the fast activation response of the piezo technology, this injector type offers a great potential for innovative injection strategies. With different strategies, one injector can produce different spray forms and so target the fuel in different spaces. One such strategy is a pulsed, or multiple injection strategy. Instead of bringing in the fuel in one long injection period, the fuel delivery is separated into several shorter injections but with the total mass remaining the same. So not only is rate shaping possible, but also spray shaping. Such a technique has a tremendous influence on the spray behaviour and the gas phase. A second possibility is a long injection with a reduced lift. Such an injection strategy produces a completely different spray. This could be an important tool to place the fuel where it is needed, as different combustion processes probably need different fuel distributions. Modern combustion strategies such as Homogeneous Compression Charge Ignition or Controlled Auto Ignition work over a narrow operating range of the engine, only. In some cases, a stratified approach could make sense while under different conditions or engine loads the classic Otto combustion makes sense. Only a specific fuel distribution allows the operation of these combustion strategies, so, to combine them in one engine, a very flexible injection system is necessary to switch very fast between the different combustion regimes.

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Experimental Facilities and Methods

The injector used for these experiments is a piezo hollow cone injector. Its outwards opening pintle is directly activated by a piezo stack. It was designed for gasoline at a rail pressure of 20 MPa. It produces a hollow cone shaped spray with a cone angle of approximately 96 degrees. The piezo injector was driven by a direct injection control unit (DICU) from ScienLab. The DICU allows a variation of needle lift and lifting speed. These can be controlled by the user in three ways. First the energy that is sent to the piezo stack can be controlled, the second possibility is to control the lift by the charge that is applied to the piezo stack and the third possibility is the voltage that is across the piezo stack. For the following experiments the Injector was controlled by the charge, two settings have been used in particular (Table 1).

Table 1. DICU settings for the pulsed and the long injection with low needle lift

Strategy	**Pulsed injection**	**Long injection**
Charge	0.5 mC	0.35 mC
Profile	Rect100	Rect100
Current	5 A	3.5 A

The charge, in millicoulombs, determines the needle lift. The more charge that is applied to the piezo, the more it expands and the more the needle is opened. The profile defines the shape of the current to the injector. The shorter the profile is, the stronger the current to the piezo the faster the needle opens. This profile is user defined, for example a trapezoid, sinusoidal, Gauss or rectangular profile can be chosen. In the present case, a rectangular profile of 100 µs length (rect100) was used to open and to close the needle. With this profile a maximum charge of 1.1 mC could be achieved, which corresponds to a maximum needle lift of approximately 40 µm. The absolute minimum opening charge is about 0.27 mC. The injection duration can be controlled by pulse width modulation. For the pulsed injection mode, the injection was split into five injections. Each pulse was 0.1ms long. As the time response to open and to close the injector are both 0.1ms long, the effective injection duration is 0.2ms long, which is the minimum injection duration for a current profile of 100 µs length. The piezo crystal was loaded with 0.5 mC, which lifts the needle a bit less than half the maximum lift. The time between the pulses was 1.425 ms (700Hz). The gasoline was under a pressure of 12 MPa. The long, continuous injection pulse lasted 1.8 ms, which gave an effective injection duration of about 1.9 ms. The charge on the piezo was set to 0.35 mC, which corresponds to a needle lift of about 5-8 µm.

With the Injection Rate Analyzer (IRA) from IAV GmbH (Berlin, Germany), the mass flow for the different injection strategies was measured and compared. The IRA is a device to measure the volume (or mass) flow through injectors. It consists of a massive body, which is filled with the fuel. In this body the injector, a pressure sensor and a thermo couple are mounted [5]. The fuel inside the IRA is pressurised. If fuel is injected through the injector, a pressure wave propagates through the fuel inside the body of the IRA. Knowing the speed of sound, tube area and the density of the fuel, the volume flow rate and mass flow rate can be calculated as shown in Figure 4.

In the present work three complementary measurement techniques have been used and spray characterisation experiments have been carried out under engine like conditions at ETH Zurich and under atmospheric conditions at Loughborough University. In the high temperature, high pressure cell, HTDZ (Table 2) in Zurich, evaporating and non evaporating conditions have been explored. As the spray penetration length is a function of density and temperature of the surrounding gas [6], measurements have been carried out at three conditions. Atmospheric conditions have been used for the PDA measurements in Loughborough and in Zurich, outside the HTDZ (pressure 1013 ±30 hPa, temperature 295 ±2 K) with a density of about 1.2 kg/m³. In the HTDZ pressure and temperature were 0.65 MPa at 303 K and 1.12 MPa at 525 K. So a constant density of 7.6 kg/m³ could be achieved, for both, evaporating and non evaporating conditions.

Table 2. Specifications of the HTDZ

Parameter	**Specification**
Diameter/Width	Ø 110 mm /40 mm
Max. Temp.	300–700K (without precombustion)
Pressure (before comb.)	0.1 - 8 MPa
Pressure (after comb.)	≤ 20 MPa

Mie imaging was used to visualize the liquid phase in a cross section through the hollow cone spray. The light sheet was produced by an Ar^+ - laser (Spectra physics) operating in multiline mode with wavelengths between 476 and 514 nm. A cylindrical lens with a focal length of -75 mm expanded the beam to a light sheet, which was refocused horizontally by a second cylindrical lens (focal length of 1000 mm) and directed through the hollow cone spray. In this way a thin and wide laser sheet could easily be produced. The scattered light was collected with a LaVision HSS 6 high speed camera with a resolution of 512×512 pixels and frame rate of 20 kHz (Figure 1, blue path with camera 2).

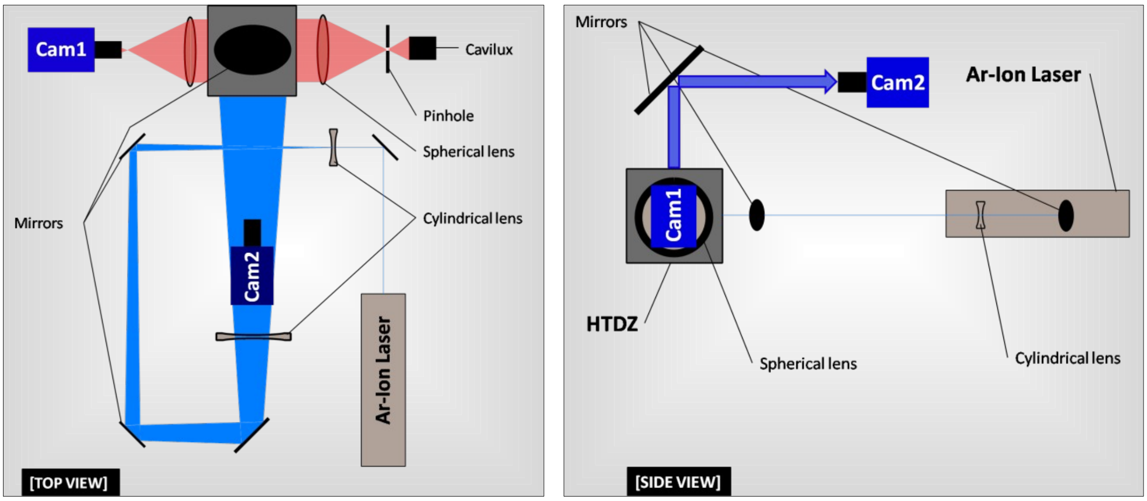

Figure 1. Sketch from the top and from the side of the two measurement systems. The Ar-Ion laser sheet for the Mie scattering (blue) and the laser light from the Cavilux®Smart diode laser for the Shadowgraphy setup (red)

Applying shadowgraphy simultaneously it was also possible to investigate both the liquid and the vapour phase of the fuel at the same time. The shadowgraphy setup consisted of a Cavilux®Smart diode laser (690 nm) with its beam expanded by a spherical lens and directed through the HTDZ after which it was refocused by an identical lens to cut off some of the refracted light in the focal point of the lens. A narrow band pass filter was used to filter out the scattered light of the Ar^+ -laser sheet. The light was collected by a second LaVision HSS 6 Camera which operated in synchronisation with the first camera, (Figure 1, red path with camera 1). In this way it was possible to simultaneously investigate the liquid phase quantitatively in a horizontal cross section using Mie scattering, and qualitatively in a vertical line of sight with Shadowgraphy. In addition the gas phase could be visualised qualitatively (under evaporating conditions, which are not shown here). A cut through the HTDZ, with the spray cone and the two light paths is shown in Figure 2.

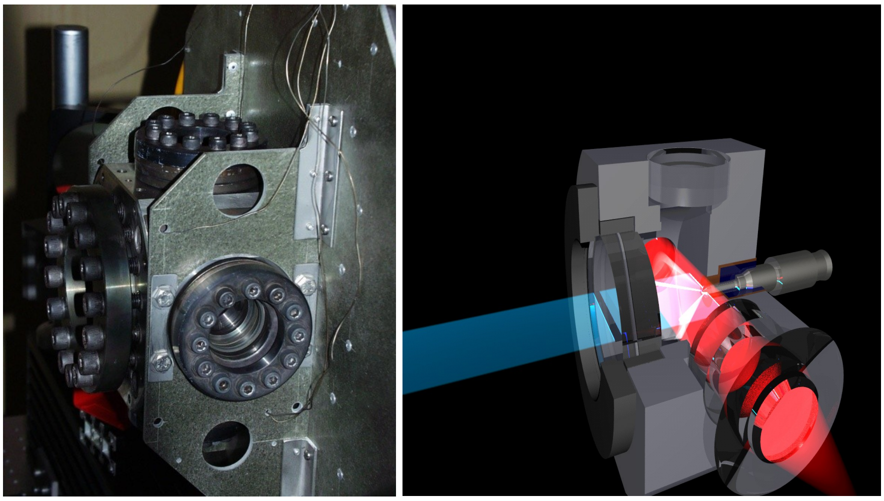

Figure 2. High temperature, high pressure cell (HTDZ) from ETH Zürich (left). Cut view with the Ar-Ion laser sheet (shown in blue) and the Shadowgraphy setup illuminating the hollow cone spray (shown in red)

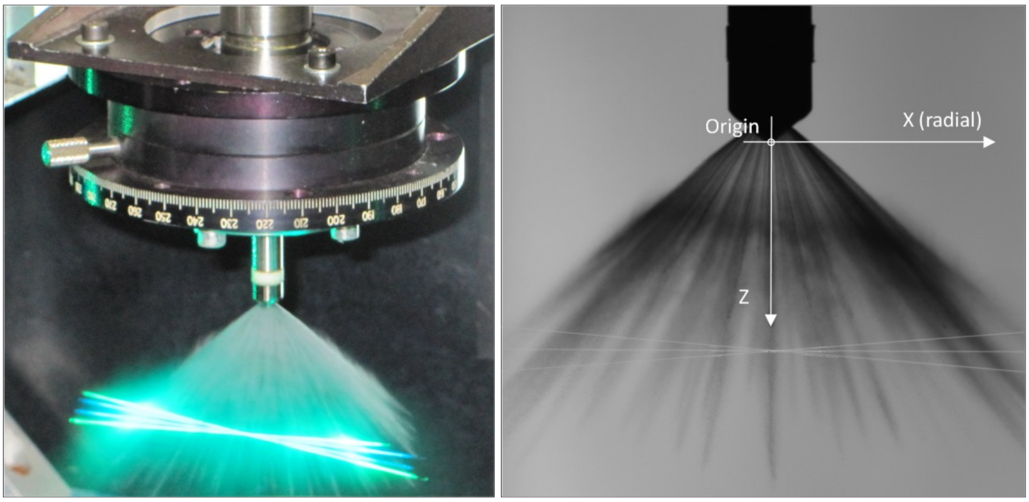

Figure 3. Injector mounted in the atmospheric spray rig at Loughborough University (left). Shadow image of the spray with crossing laser beams to look over the streaks going through measurement volume and the coordinate system with the origin directly on the needle tip (right)

In the atmospheric spray rig at Loughborough University 2D phase Doppler measurements were performed to produce the droplet size and axial and radial velocity fields as a function of time and space. The injector is rigidly held in a rotation stage, mounted on a precision 3 dimension orthogonal traverse system. The measurement origin started at a z position (in mm from the needle tip) directly under the tip (z = x = 0 mm). In a defined grid, the injector was traversed electronically along its x axis. This way the spray was moved through the laser beams on a radial path. Figure 3 shows an image of the PDA-injector setup. On the left picture the spray, mounted on the traverse system, the crossing laser beams forming the measurement volume and the spray can be seen.

To have a control where the spray is compared to the measurement volume, a flash screen was mounted behind the spray, with a PCO Sensicam taking shadow images of the spray and the crossed laser beams (Figure 3, right image). The PDA system uses an Ar^+ -laser type Coherent INNOVA-90-4 to produce two beams, blue (λ = 488 nm) for the radial velocity component and green (λ = 514 nm) for the axial velocity component. As a receiver the Dantec 57X10 was used.
gives an overview over the settings and specifications of the PDA system. For the PDA measurements, the rig was driven for 50 seconds at a frequency of 5 Hz.

Table 3. Specifications of the PDA system

Laser Transmission System	**Unit**	**Axial**	**Radial**	**Receiver**	**Unit**	
Wavelength	[nm]	514.5	488	Phase Factor	[deg/ µm]	4.6
Beam Power	[mW]	200	100	Max. Drop Size Range	[µm]	100
Beam Diameter	[mm]	5.0	5.0	Lens Focal Length	[mm]	310
Beam Separation	[mm]	50.0	50.0	Lens Aperture	[mm]	80
Polarization Plane	[-]	Parallel	Parallel	Scattering Angle	[deg]	70
Front Lens Focal Length	[mm]	300	300	Refractive Index	[-]	1.47
Measurement Volume Diameter	[µm]	39	37			
Fringe Spacing	[µm]	3.1	2.9	**Processor**		
Velocity Measurement Range	[m/s]	-30.9 to 108.4	-30.9 to 108.4	Bandwidth	[MHz]	45

Results and Discussion

Measurements with the IRA show the differences between the injection strategies in detail. Figure 4 shows the injection rate in mg/ms, over time. The signal for injection (SiOI) was sent 1ms after the start of the experiment. Therefore the hydraulic delay is about 100 µs long (depends on charge on injector). For the pulsed injection a frequency of 700 Hz was applied. Clearly visible is the difference in the maximum mass flow, shortly after the start of injection. For the pulsed injection (gray curve) the needle closes again after 0.2 ms. With the profile used to lift the needle (rect100), the needle was closed immediately after it was opened. The injection with the small needle lift raises fast, too, up to 6.8 mg/ms, but then falls back to a stable value of approximately 4 mg/ms.

To achieve comparable results, the injection duration for the small needle lift was set to 1.8 ms. This results in an injected mass of about 7.5 mg for both strategies, which gives, assuming constant railpressure and backpressure, the same total momentum, brought into the system.

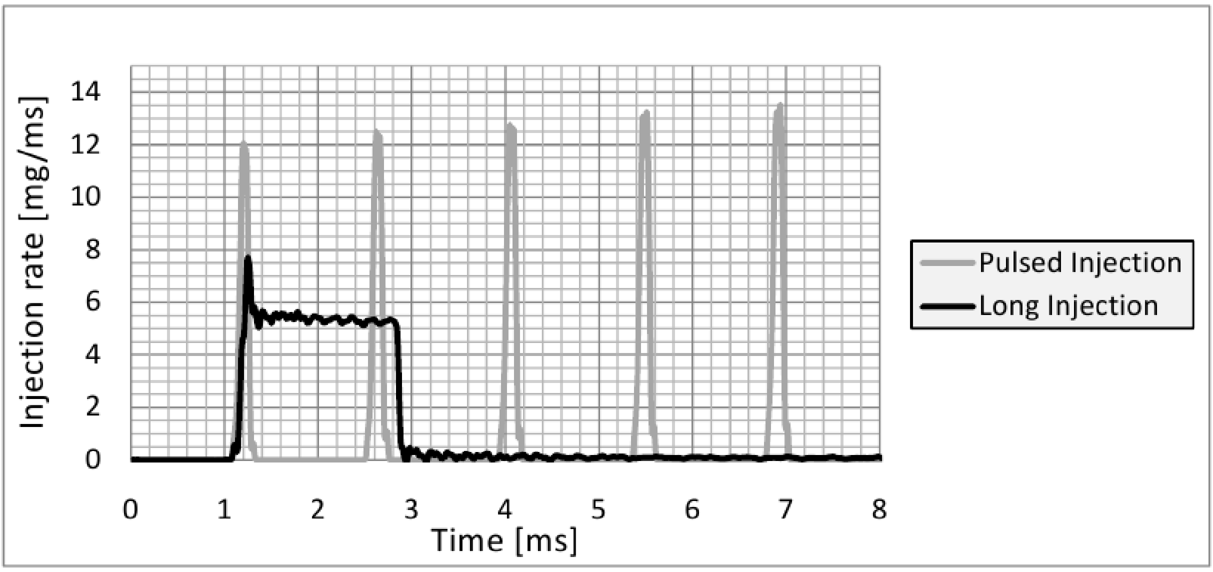

Figure 4. Injection Rate for the two Injection strategies (identical injected fuel mass); the pulsed injection (gray) and the continuous injection with reduced lift (black)

The engineering goal was to produce a spray confined to the region below the injector tip. With a multiple injection strategy this was readily achieved. Compared to a continuously propagating spray with a longer injection period, the sprays for each short injection literally come to a standstill once the injection pulse stopped. Due to the entrainment produced by the short injection pulse, a large toroidal recirculation zone is formed just below the nozzle as it can be seen in Figure 5. Its lifetime is sufficiently long so that the following droplets re-enforce the recirculation to confine the spray. The zones directly under the injector and below the recirculation are almost void of fuel droplets. These spray features can be seen on the Mie and Shadowgraphy images taken in the HTDZ (Figure 5). The Mie images have been averaged over ten realizations whereas the shadowgraphy images are from a single experiment. The timing corresponds to an external signal, as shown in the rate analysis (Figure 4).

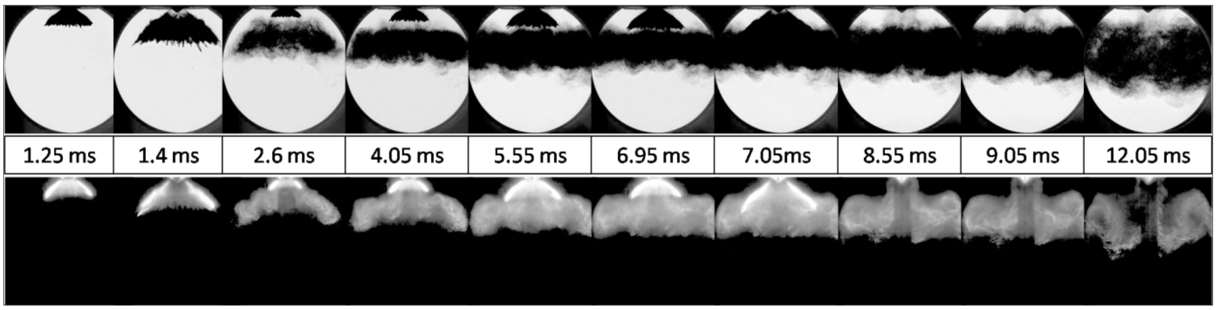

Figure 5. Shadowgraphy (top) and Mie images (bottom) of the pulsed injection under non evaporating conditions. Rail pressure 12.7 MPa, backpressure 0.64 MPa, temperature 300 K

The spray exits the injector for a very short period and due to the momentum exchange with the surrounding gas, the droplets have a very limited penetration. As can be seen in Figure 5 on the picture at time 2.6 ms (1.8 ms after Signal Of Injection) the liquid phase forms a cloud of droplets below the injector. Every single injection of the five pulses has to overcome the momentum exchange anew. By doing so, every pulse delivers more energy to a toroidal vortex which is located on the outer edge of the spray tip. The formation of this vortex needs further investigation, but it appears to build up in a very early stage of the injection. Strong vortices entrain the droplets and drag them towards the nozzle and sideways into the large toroidal vortex. Under atmospheric conditions this behaviour could be observed too, but not so strongly. Figure 6 shows the position of the PDA measurement volume. Relative to the injector tip it is situated 20 mm underneath the injector, along the injector axis. The radial position was 20 mm from the injector axis. The image was taken under atmospheric conditions. The time of the frame is 2.95 ms (1.95 ms after SiOI). It can be seen how the third injection pulse penetrates into an existing cloud of droplets. This leads to the question how these droplets influence the spray behaviour of the following injections. Firstly, the question about the number and size of the residual droplets has to be answered. Figure 7 gives an overview over the sample number (gray) and droplet size D10 (black). For the PDA measurement the injector was driven at a frequency of 5 Hz for 50 s. This way 250 experiments, each containing a burst of 5 single injections, could be recorded. It can easily be seen that the maximum sample number for each of the five injections is more or less constant. This can be interpreted as no coalescence is taking place, especially since the drop size also stays constant. The droplet sizes show a clear behaviour. In the tip of the spray big droplets up to Ø32 µm can be seen. These big drops decay very quickly due to the high shear stress evoked by the high velocity which can be seen in (Figure 8) .

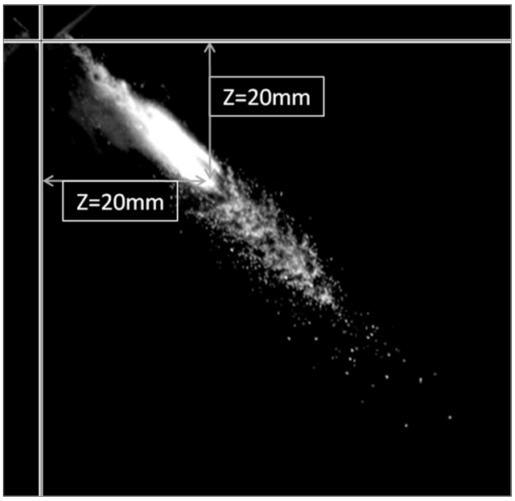

Figure 6. Burst in atmospheric conditions, shortly after the end of the 3rd injection pulse. The lines indicate the position of the origin and the arrows indicate the position of the PDA measurement volume

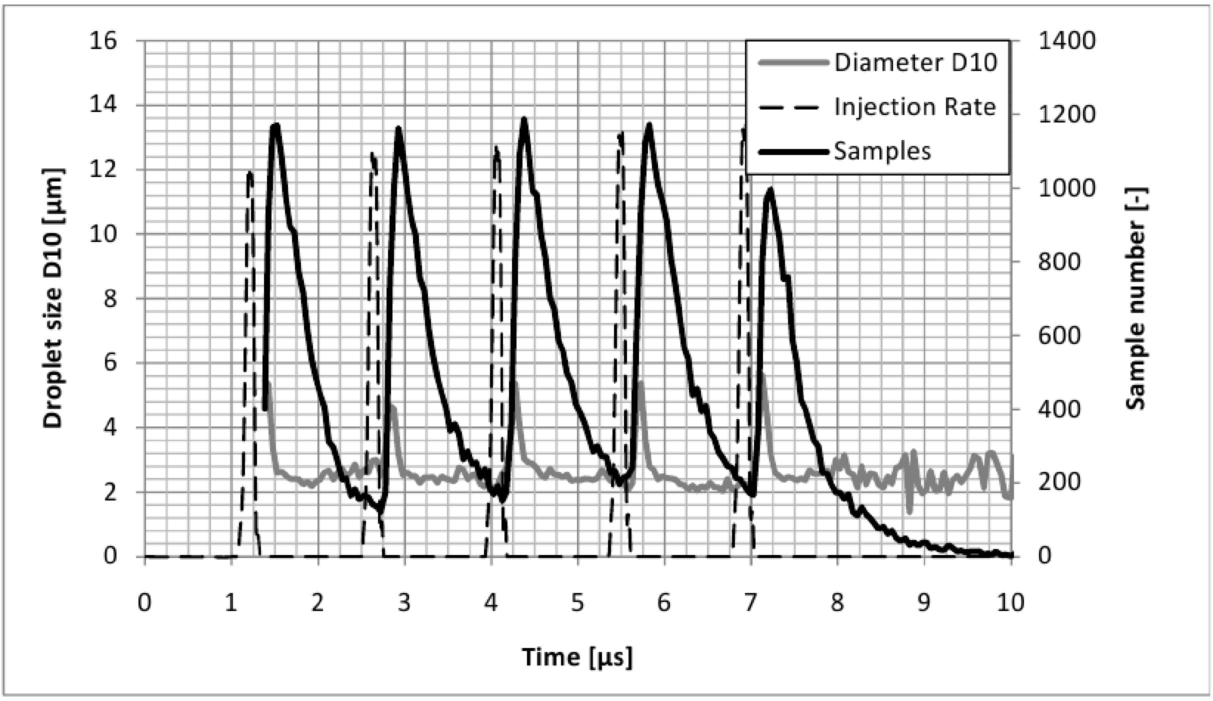

Figure 7. Drop size measurements from 250 injections (250 injections of 5 bursts), pulsed injection. Droplet size (black) and sample number (gray) of all 250 injections (Time bin = 50 µs)

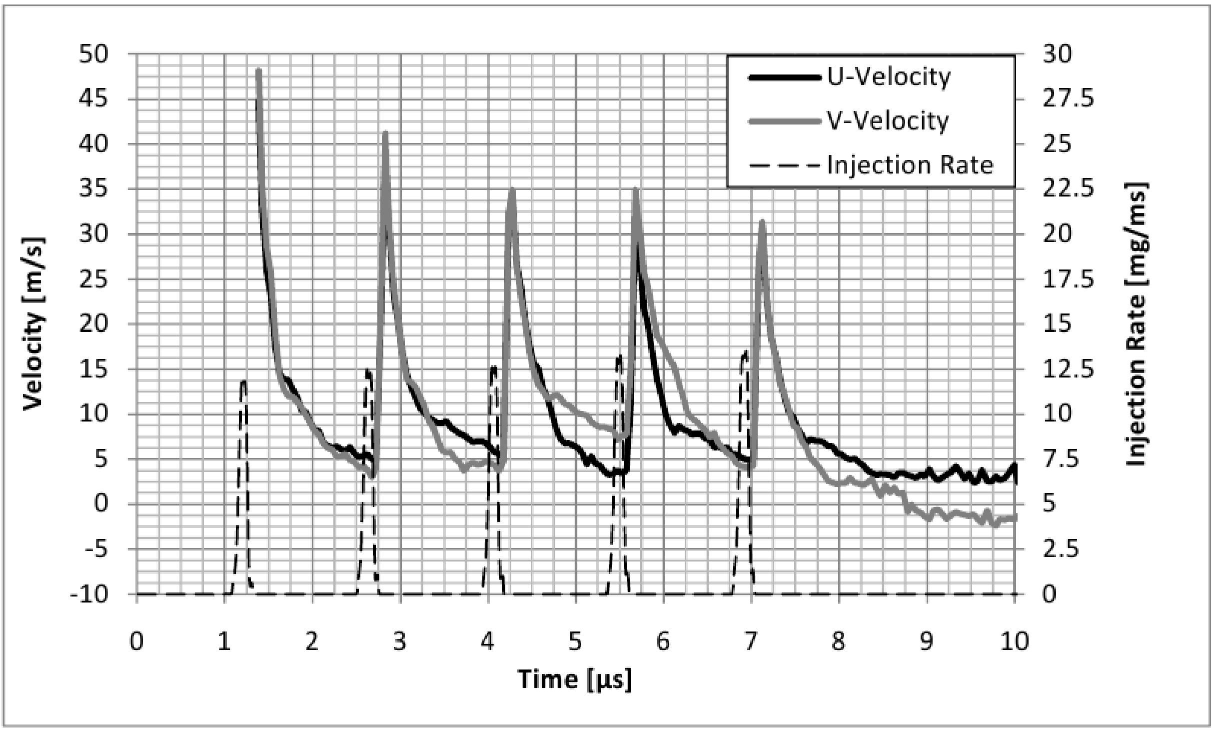

Figure 8. Droplet velocity measurement from 250 injections (250 injections of 5 bursts), pulsed injection. Axial (black) and radial velocity (gray) for the pulsed injection (Time bin = 50 µs)

The development of the spray for the continuous injection, Figure 9, highlights the difference in spray shapes. The first part of the injection is very similar to the pulsed injection. If we compare the time after end of injection in the spray images (2.95 ms for the continuous and 7.05 ms for the pulsed injection) of both techniques, it is clearly visible how the continuous injection propagates forward much faster (along the injector axis). The dense zone of droplets which is built up underneath the injector in the case of the pulsed injection gets pulled further downstream in comparison to the pulsed spray. The toroidal vortex is located lower under the injector and more towards the inside of the cone. This leads to a strong channelling of the droplets down along the injectors axis, as can easily be seen in Figure 9.

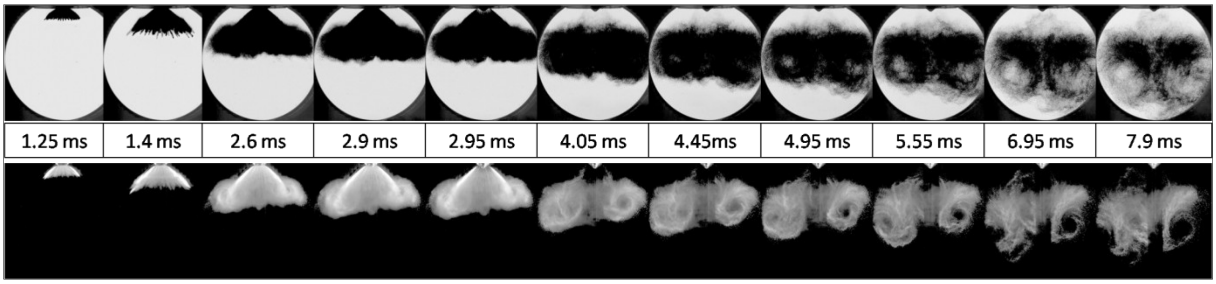

Figure 9. Mie and Shadowgraphy images of the spray development over time of the continuous injection. Rail pressure 12.7 MPa, backpressure 0.64 MPa, temperature 300 K

The PDA data for the reduced needle lift (Figure 10) shows that the droplets are smaller for the reduced needle lift. But once the dense spray has left the observation volume, the residual droplets are about the same size in both cases. Comparing the velocities (Figure 11) it can be seen that the peak velocities are smaller in the case of lower needle lift. So the velocities and the droplet sizes are reduced. Interesting is the part after the end of injection. The velocities for the continuous injection show a big recirculation zone directly following the dense spray. The pulsed injection shows at the same position, at the same time after the injection, only a hesitant change in the direction of the velocity. This is probably the vortex that is channelling the droplets in the case of the continuous injection and keeps the droplets in place for the pulsed injection.

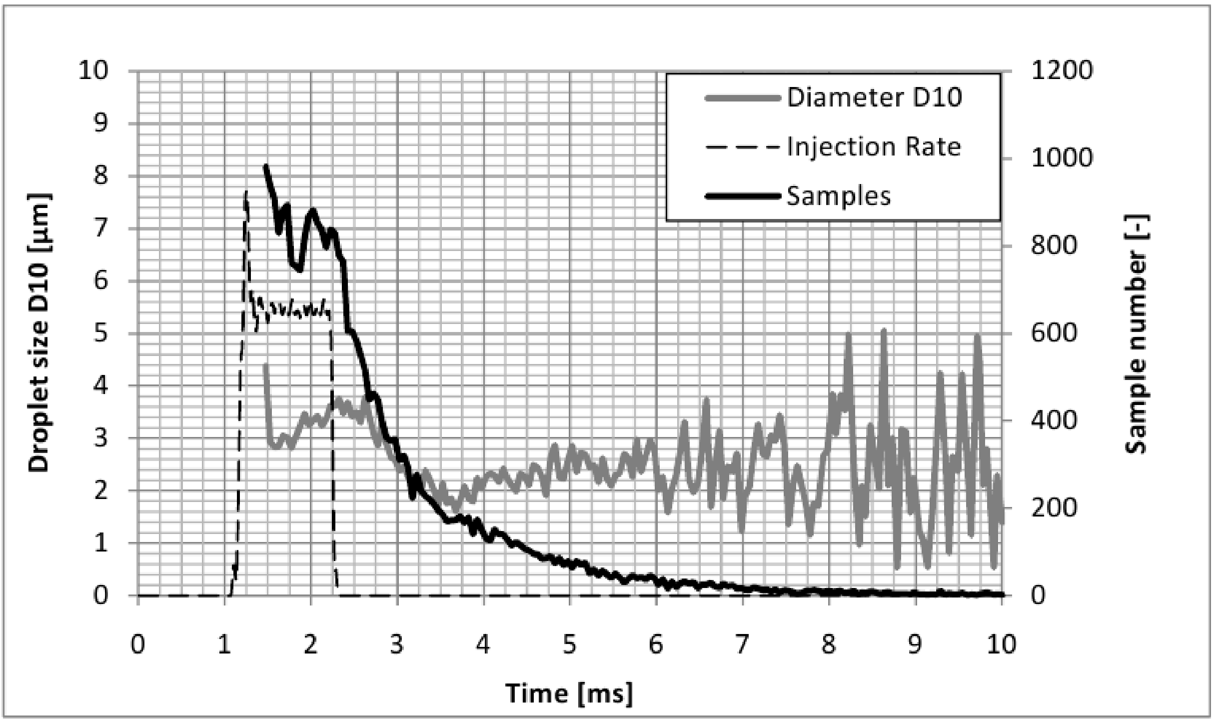

Figure 10. Droplet size measurement from 250 injections (250 injections of 5 bursts) for the continuous injection. Droplet size (black) and sample number (gray) of all 250 injections (Time bin = 50 µs)

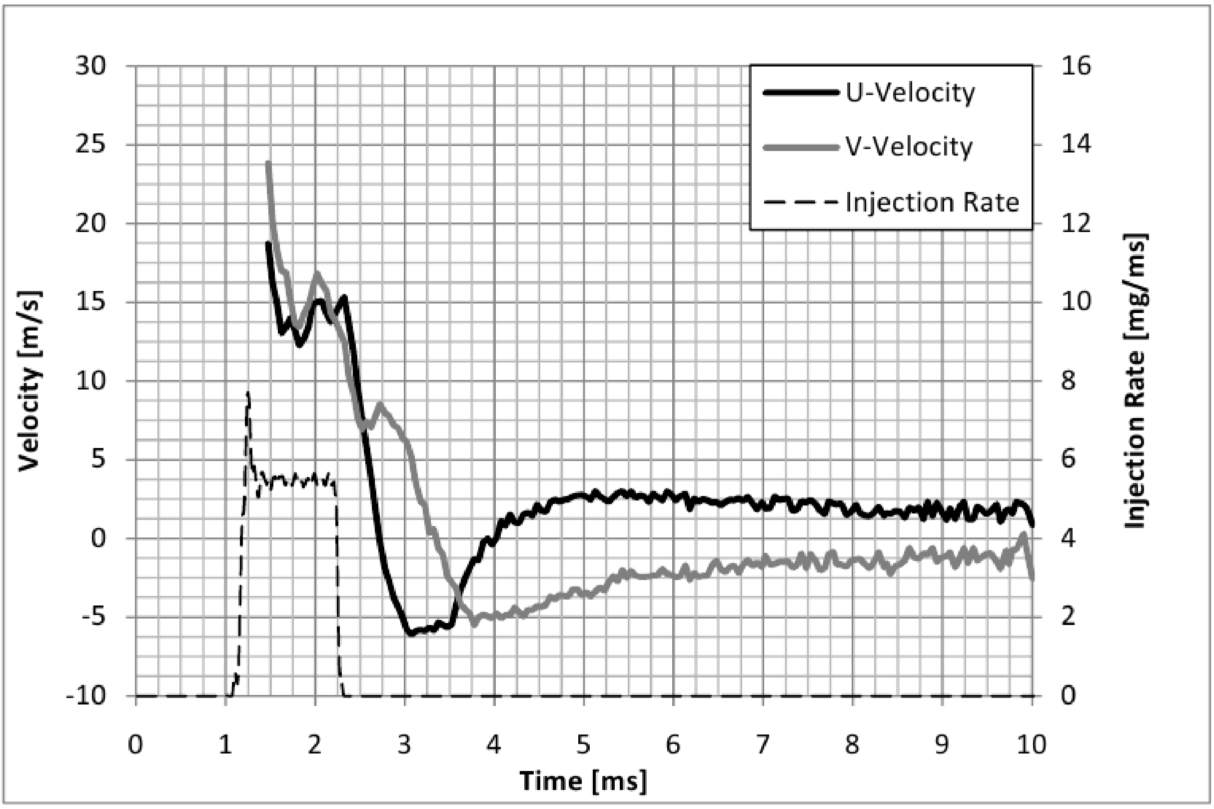

Figure 11. Axial (black) and radial velocity (gray) for the continuous injection

Conclusions

Two different injection strategies have been applied to a piezo hollow cone injector while keeping the injected mass and injection pressure constant. One strategy works with a long single injection duration at a reduced needle lift while the second implements a multiple injection strategy consisting of five short injections with a medium lift. It was shown that these different injection strategies lead to different shapes of the spray and different degrees of homogenisation.

Therefore, only simple changes are needed to the injector drive, which can be applied during operation, to provide a field of different spray shapes with just one injector. In this way, different combustion strategies, e.g. stratified or homogenous combustion, can be applied and optimised for different engine load points with the same hardware.

The influence on the size of the droplets produced in the dense parts of the two different sprays could not be fully answered, but in the residual droplets no difference in size could be seen, i.e. the difference in vaporisation of the two sprays should be of no consequence. The large, near static, vortices generated for the multiple injection strategy are the cause of the difference in the behaviour of the spray, what remains, is to understand how these are built up and how they can be influenced to improve combustion efficiency.

Outlook

Further investigations on the behaviour of the spray are planned. So the question about the source of the forming of the circular vertices has to be answered. There is experimental data under evaporating conditions available which need to be investigated to understand the influence of the evaporation on the spray shape. Another question to be answered is the influence of the pulse frequency on the behaviour of the spray. What changes if the needle lift is increased and the pulse duration is reduced? What is the influence on the evaporation?

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