# Effect of injection conditions on penetration and drop size of HCCI Diesel sprays

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**Abstract.** The development of direct injection strategies in modern Diesel engines needs increasingly high injection pressures and better fuel distribution in the combustion chamber. The ongoing study of the HCCI concept will probably require early fuel injection in air at low pressure and density, and also fuel composition will probably require some modification to reach a perfect mixing and to match evaporation and ignition requirements. In this work different common rail nozzles, fed with fuel supplied at constant pressure in the range from 30 to 100 MPa, are used to produce sprays in air at ambient temperature and pressure ranging from 1 to 7 bar, to investigate the spray penetration as a function of air and fuel pressure. From experimental results a scale low is then deduced, which is able to account for different penetration curves in the various tests by a unique common behaviour: a linear penetration part, whose length is function of the air density and of the nozzle diameter, followed by a decrease of the tip velocity. For a reduced set of experimental conditions drop size and velocity are measured by phase Doppler anemometry; time averaged mean diameter is then computed and analysed as a function of the fuel injection pressure, and shows a clear reduction of the drop diameter with increasing injection pressure.

## 1. Introduction

The development of direct injection strategy in modern Diesel engines needs increasingly high injection pressures and better fuel distribution in the combustion chamber. The key parameters used to select the most appropriate fuel injector are the spray penetration and drop size distribution. These parameters control the spray fluid dynamics and droplet evaporation and are commonly used to compare experimental data with model predictions. Both, spray penetration and drop size depend on the injection pressure, when ambient gas density and temperature are fixed. In a previous work [2] we studied the effects of gas density on Diesel spray penetration; different laser-based techniques were applied and the analysis of a large number of data allowed to propose a general correlation based on proper scaling of space, time and velocity. Nowadays a new interest is arising, derived from the concept of HCCI engine [7], where part of the fuel could be injected in the induction stroke or at the beginning of the compression stroke, when air temperature and density are much lower than in a conventional Diesel engine, and fuel could be reformulated to enhance evaporation and to control the ignition timing and the combustion rate. New information is necessary about high pressure Diesel spray injected in air at low density and temperature.

A set of common rail injectors, with different nozzle diameters and configuration, was used to study spray penetration with injection pressures from 30 MPa to 100 MPa. Fuel was injected in a constant volume chamber filled with quiescent air at room temperature, with air pressur ranging from 1 to 7 bar.

The spray penetration was measured by a digital visualization system with a CCD camera and flash illumination, with exposure times of 1 μs. A pre-processing of the images was performed by subtracting background noise and enhancing the spray contours, then spray length was measured by. The accuracy in estimating the spray tip position was evaluated to be about 0.3 mm, which was considered sufficient for the present purposes.

The next step has been a detailed investigation on the effect of the injection pressure to understand its relevance on tip penetration and drop size distribution. The Phase-Doppler technique was used to measure drop size distribution inside the spray, at downstream locations relevant for engine applications, where the drop number density allowed reliable measurements. The data acquisition, triggered by each injection, was performed over a period longer than the injection duration. Phase averaging was performed later by collecting data into 0.1 ms time slots. Correlation between drop velocity and size has been also investigated to verify droplet equilibrium with the gas phase.

The penetration results were compared with previous data and data found in the literature [2, 12], looking for a general correlation and scaling laws. The scaling laws allow a convenient definition of the near field and far field region in a Diesel spray. Although the present results hold only for non-evaporating sprays injected into quiescent gas and should not be extrapolated directly to real engine conditions, it is reasonable to expect that the results have some interesting implication for penetration prediction and, more generally, for Diesel spray modeling.

## 2 Experimental set-up

Different injectors were tested to produce spray in a constant volume pressurized chamber, where measurements were performed by digital photography and phase Doppler anemometry. The experimental set-up is described hereafter.

### 2.1 Injection system

Fuel was supplied at constant pressure by an air booster pump, and fed to the injector through a flexible line. Fuel pressure was set at 30, 50 or 100 Mpa. Standard common rail injector holders, with purposely made nozzle were used, as reported in table 1. The injector command duration was set at 2 ms.

**Table 1:** list of injectors and nozzles

| Nozzle | Injector holder | hole number and diameter | Holes disposition | Use |
|---|---|---|---|---|
| 1 | A | 10x80 μm | Cone 150° aperture | Images for tip penetration |
| 2 | B | 10x100 μm | Cone 150° aperture | Images for tip penetration |
| 3 | C | 5x125 μm | Cone 150° aperture | Images for tip penetration |
| 4 | D | 5x130 μm | Cone 150° aperture | Images for tip penetration |
| 5 | D | 8x100 μm | Cone 150° aperture | Images for tip penetration |
| 6 | E | 1x80 μm | Axial | PDA measurements |

### 2.2 Pressurised vassel

The sprays were injected into a cylindrical chamber, internal diameter 206 mm, equipped with four apertures on the lateral surface, which can be closed or equipped with quartz windows. The apparatus had been already described in previously reported works [2, 8] and here it was used with some enhancements.

The pressure chamber was set vertically, as shown in the fig. 1, with the injector on the top if equipped with a single-hole injector for PDA measurements, or with the injector set horizontally from the back side for multi-hole nozzle, and the CCD camera set with the optic axis perpendicular to the spray plume, which is illuminated by two stroboscopic lamps from both sides.

### 2.3 Visualization system

A high-speed single-frame CCD Camera (PCO SensiCam, 1280x1024 pixels, minimum exposure time 0.1 μs) was used to acquire images of the spray.

Two stroboscopic lamps, 850 mJ flash energy and 10 μs duration (Bint 850 ST), were used to illuminate the spray from both sides. The camera exposure time, 1 μs, was positioned in the moment of maximum intensity of the flash, 7 μs from its actuation signal.

In all cases each image is recorded from a different injection, that means that a sequence is not cycle resolved. At each delay, 10 images are recorded for better statistical analysis. In the data acquisition process the time scale is referred to the beginning of the injection opening signal, which is used to trigger the system. The real opening and closing of the injector always show a small delay (0.3 – 0.4 ms depending on the fuel pressure) from the electronic signal.

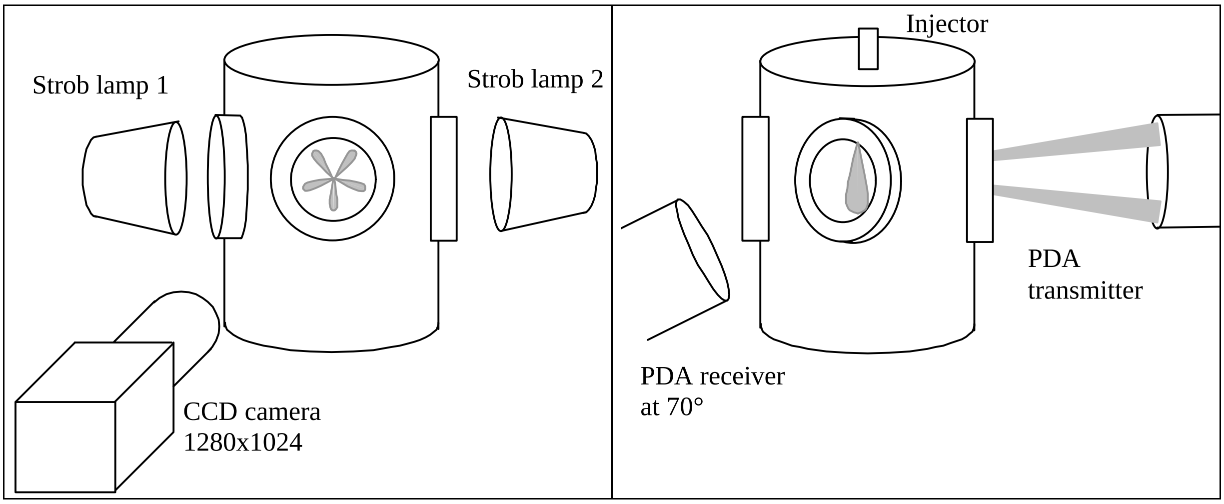


**Fig. 1.** Photographic set-up and PDA set-up

### 2.4 PDA system

A commercial Phase Doppler Anemometer (Dantec PDA) was used to measure droplet size and axial velocity. The instrument configuration is reported in table 2.

**Table 2:** PDA system configuration

| Transmitting optics | |
|---|---|
| Laser wavelength | 514 nm (green) |
| Laser beam diameter at the front lens | 2.45 mm |
| Laser beam separation at the front lens | 70 mm |
| Front lens focal length | 600 mm |
| Nominal measurement volume diameter (1/e$^2$) | 160 micron |
| Fringe distance | 4.4 µm |
| Receiving optics | |
| Scattering angle | 70° |
| Lens focal length | 310 mm |
| Sensor opening distance, measured by the regulation micrometer | 2 mm (maximum) |
| Electronics | |
| Frequency shift | 40 Mhz |
| Velocity range | From -26 to 132 m/s |
| Diameter range | 1 – 82 µm |

### 2.5 Experimental conditions

Experimental conditions were varied, by changing the fuel and the air pressure, as reported in table 3, for each of the tested nozzles..

Fuel pressure was chose to three different values in the range typical of common rail injection systems.

Air pressure was chosen in the range from 1 to 7 bar, which should be the range of air pressure for HCCI combustion that has started to be studied and tested [7], and is a range of conditions for which few information is available since it is far from the usual working gas density of conventional Diesel application.

In this situation with low air density and low temperature, it is expected that spray penetration is much faster for a longer path than in high density evaporating environment, so wall impact could occurs very easily. For this reason nozzle diameters were chosen in the lowest range nowadays available, since it is expected that a small diameter shortens the penetration of the spray, and decreases the drop diameter, which enhances the fuel evaporation [11].

**Table 3:** experimental conditions for photographic analysis

| | |
|---|---|
| Fuel pressure | 30, 50, 100 Mpa |
| Air pressure | 1, 2, 3, 5, 7 bar (absolute) |
| Air temperature | Ambient |
| Injection repetition rate | 1 Hz or less |
| Injection duration command | 2 ms |
| Injection opening delay | 0.3-0.4 ms, depending on fuel pressure |
| Injection closing delay | 0.3-0.4 ms, depending on fuel pressure |
| Photo delay (from the electronic trigger) | From 0.3 to 2.5 ms, variable step |
| Number of photo for average measurements | 10 per each delay |

The time step between the picture series was variable, shorter for faster penetration to capture at least ten complete images of the spray in the observed field, which is about 80 millimeters.

PDA measurement were performed only with single hole injectors, since it had already be ascertained that the behavior a single spray does not depend on the presence of the other sprays, if they are enough distant as in standard multi-hole injectors. To operate the PDA in optimal conditions by reducing all sources of noise [3], even the unpredictable effect of window dirtying, the quartz windows were removed from the chamber, so that only measurements at ambient air pressure were performed.

Results issued from the large diameter nozzle were in general of lower quality than those issued from very small nozzles. From a large hole, a larger amount of fuel is injected, thus producing a spray with higher droplet concentration, and hence optical opacity. The capacity of the PDA system to measure in such an environment is limited, and even if velocity measurements could still be reliable, a sensible shift toward large value is expected in the droplet size average value [3], because of the loss of small droplets. In our case only the results for the 80 micron hole nozzles were considered reliable to compare quantitatively, and not only qualitatively, the drop size results.

## 3 Photographic results and spray penetration

Digital photography was used to acquire spray images at different delays from the injection trigger and to measure the spray length, which is the measure of the tip penetration.

### 3.1 Images processing and Penetration results

The enormous number of pictures, over 2000 per each tested nozzle, required the use of an automated image processing software to extract the desired information. Each image was pre-processed with a background subtraction procedure, then each spray in the picture was isolated and its length measured by a simple algorithm [5] which showed to be very robust as regard the spray length measure. Results where then averaged among different images taken at the same delay, and if available also among two or three different sprays generated by the same multi-hole nozzle.

Penetration results are shown in fig. 2, where the average spray length is expressed as a function of the time delay, and the governing parameter is the air pressure. Each graph refers to a different injection pressure and one nozzle diameter.

Penetration curves show a common pattern: a first part of the curve, showing nearly constant velocity, is then followed by a decreasing velocity part.

At the very beginning of the linear part of the penetration curve, a very short portion of it shows that the tip velocity increases before it reaches the constant value; this is generally explained by the higher load loses attained during the opening phase of the injector needle [8].

The inclination of the linear path, that means the spray tip initial velocity, is function of the fuel pressure, as it is normally expected, and in a minor way it depends also on the nozzle. This point will be discussed in a later paragraph.

The length of the linear part is shorter at increasing air density, but doesn’t change with the fuel pressure. It is also function of the injector nozzle, scaling nearly linearly with the orifice diameter.

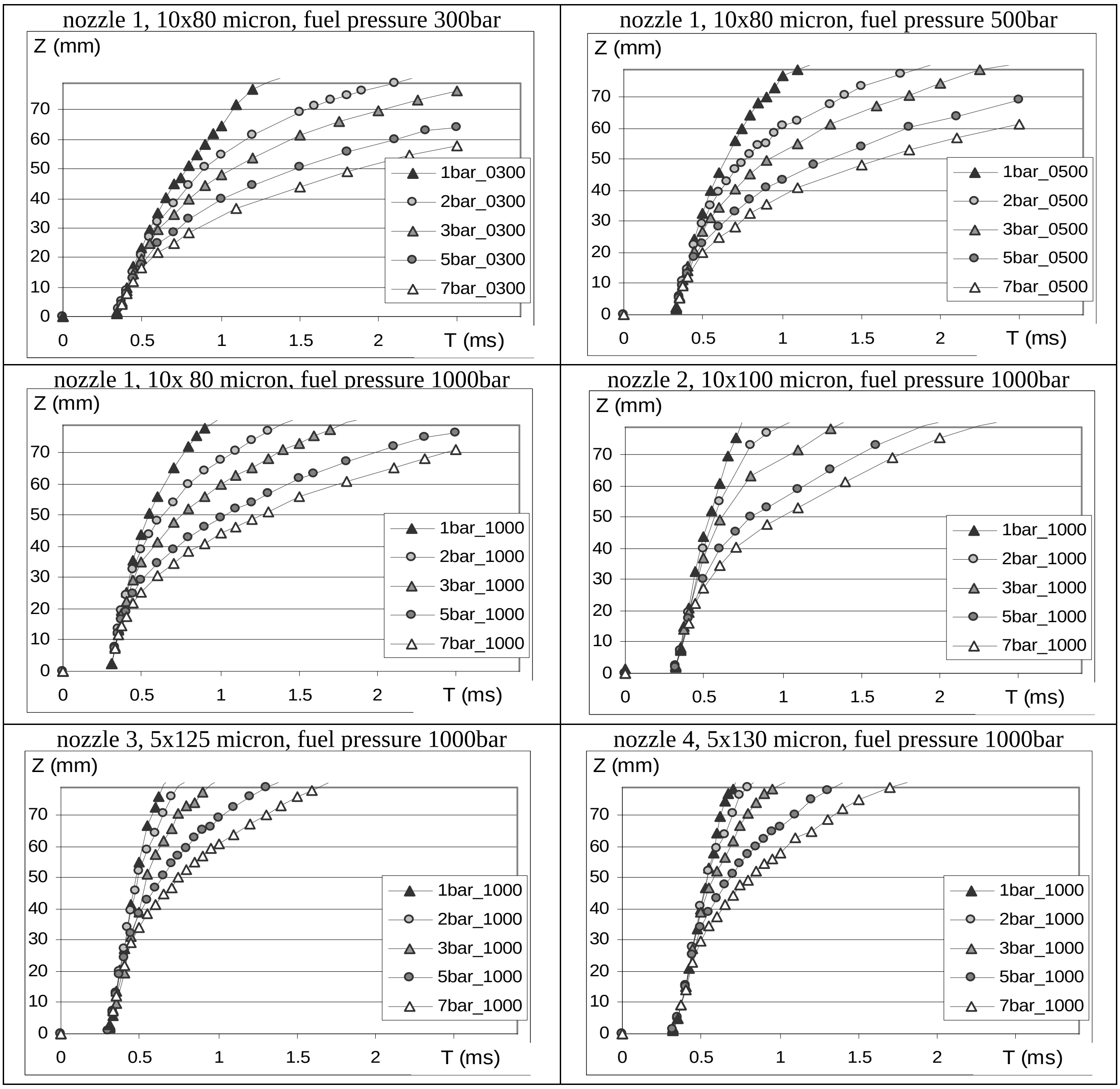


**Fig. 2.** Exempla of spray tip penetration for different orifice diameter and experimental conditions

### 3.3 Data reduction, adimensionalization

The considerations on the pattern similitude of the penetration curves, and of the dependence on the operative parameters, suggest the presence a scaling low able to collapse the penetration curves all together in a narrow band when displayed on the rescaled dimensions, as it was already found by many other autors [12, 9]

In our work, the scaling equations where chosen as reported in the following equations:

$$T_{ad} = (T-T_0) * V_0 / D_0 * (\rho_{air} / \rho_0)^{\alpha} \qquad Z_{ad} = Z / D_0 * (\rho_{air} / \rho_0)^{\beta} \qquad (1)$$

Where:

- T is the time elapsed from the injection trigger (at which spray images were taken)
- Z is the length of the spray at the time T (measured from the digital image)
- $V_0$ is the initial tip speed measured by linear interpolation of the linear part of the penetration curve
- $T_0$ is the injection delay from the trigger (the intercept of the line used to measure $V_0$ with the time axis)
- $D_0$ is the orifice diameter
- $\rho_{air}$ is the air density in the test chamber
- $\rho_0$ is the air density at ambient conditions
- $\alpha$ and $\beta$ are the exponent of the air density to be found by optimization of the scaling equation results.

Since only one kind of fuel was used in the present study, it is impossible to evaluate the effect of the fuel density on the penetration law, so this parameter is not considered and only the air density is present in the formulas.

The optimization of the data reduction by variation of $\alpha$ and $\beta$, to superimpose all the penetration curves, led to the value $\alpha = \beta = 0.6$ ; the results after rescaling are presented in figure 3.

All data were scaled and resulted in a narrow band whit a common behavior in the new co-ordinates $T_{ad}$ and $Z_{ad}$, which can be used to extrapolate the penetration curves in different conditions of air density, injection velocity and nozzle diameter.

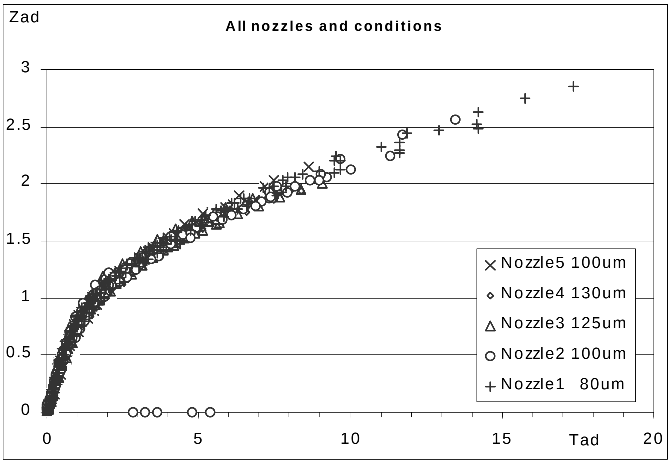


**Fig. 3.** All penetration results after scaling by formulas (1) and (2)

### 3.4 Considerations on the pressure-velocity correlation

As it was already introduced, the tip velocity in the linear part of the penetration curve was found to be a function not only of the injection pressure, as it is normally expected from Bernoulli's formula, but in some unknown way of the injector in use.

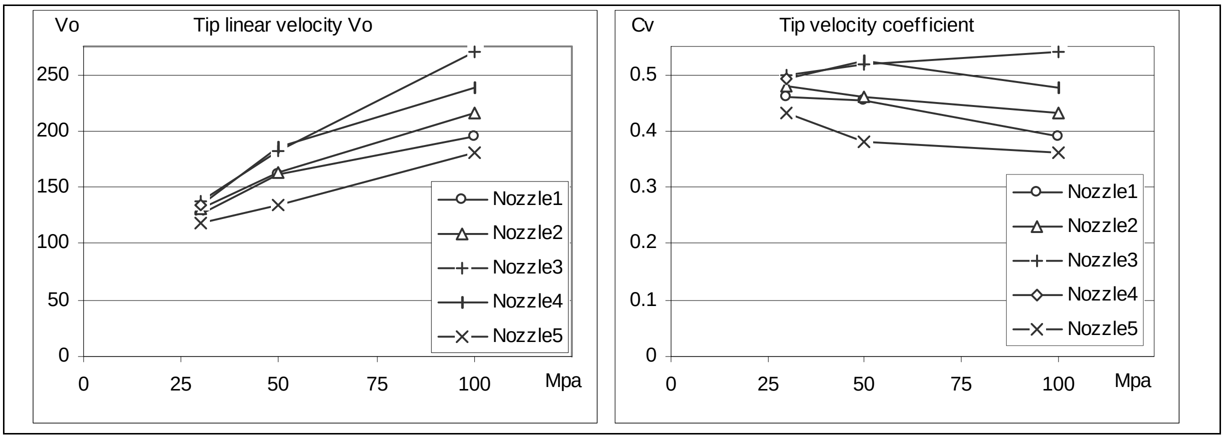


**Fig. 4.** Spray tip velocity in the linear part of the penetration curve $V_0$, and corresponding velocity coefficient

Different tests with the same injector holder and different nozzles excluded the influence of the holder only, or of the orifice diameter only. Also the ratio of the injection velocity to Bernoulli ideal velocity was not constant, so that a common velocity coefficient couldn't be used. Probably this should have been possible if the pressure of the fuel in the injector sac, just before the orifices, had been known, but it was not our case. So our only possibility was to measure the tip linear velocity $V_0$ and to use it for our rescaling formulas, and to draw the conclusion that the knowledge of the fuel pressure only in the rail, without its value on the nozzle sac nor a way to evaluate it with a given injector-nozzle assembly, introduces strong uncertainty in the spray penetration prediction. Figure 4 shows differences from the lowest to the highest value of the measured $V_0$ of 16% 37% and 50% respectively at 30, 50 and 100 Mpa fuel pressure in the rail. The use of $V_0$ is a way to skip all these problems and to go directly to the spray penetration prediction. It is important to note that, especially for the smallest nozzle holes, $V_0$ is better evaluated at ambient air pressure, where the linear part of the penetration curve is longer. More, in this condition the measure of $V_0$ it is quite simple and achievable by different techniques [4]

## 4 PDA results

Phase Doppler anemometry was used to measure the velocity and size of the injected drops, with time resolution of 1 microsecond. The results reported here were collected from the spray issued from the 80 micron single hole nozzle. Measurements were performed about the spray at 50 mm from the injector tip, since at a closer distance to the injector measurements were less reliable, for excessive droplet concentration. At this distance also the drop velocity has decreased, and allows the use a shorter focal lens length in the PDA transmitting optic, thus decreasing the dimension of the measurement volume, and enhancing again the result validation.

For each injection pressure, 21 locations were chosen for the measurements, disposed along two perpendicular diameters of the spray cross section, whit a step of one millimeter. Injection duration was set at 1 ms, and data were collected in a 3 millisecond time window, starting from the injection trigger; many successive injections were repeated to collect 30’000 data at each location.

Data included droplet axial velocity, diameter and arrival time counting from the injection trigger. The first step of post processing has been a calibration of the correlation between droplet diameter and measurement volume dimension [1], then time averaged results were computed in time slots 0.2 ms long, with weighting based on the previously found correlation. The computed values are the axial average velocity $U_{vel}$, and the average droplet diameter $D_{10}$, $D_{20}$, $D_{30}$ and $D_{32}$.

### 4.1 Results and discussion

An example of velocity and size results is reported in fig. 5. The time scale is from the injection trigger, and the time required to observe the first droplets account for the injector opening delay and for the convection time to the measurement location

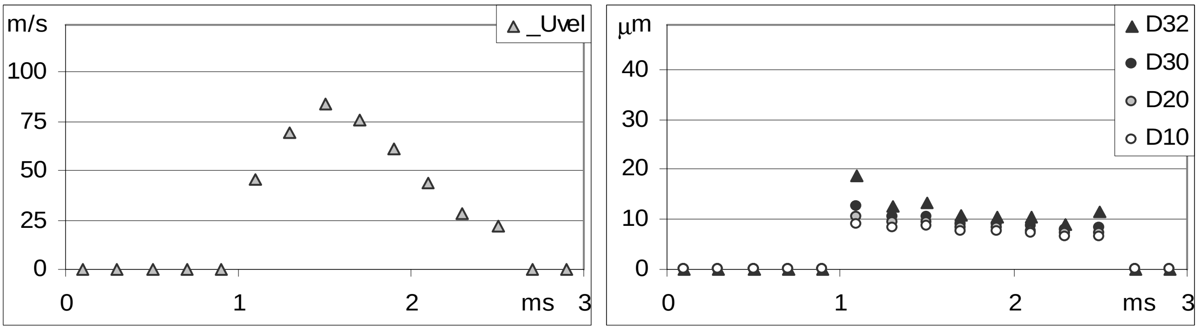
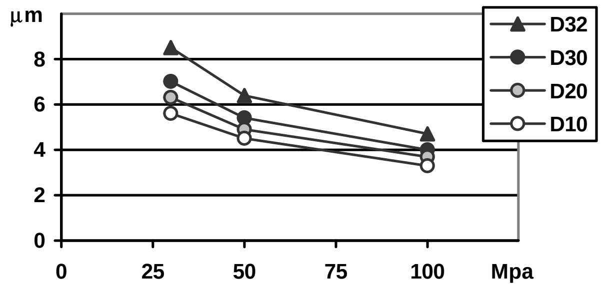


**Fig. 5.** Injector nozzle 120 micron, P = 300 bar, Z = 50mm, R = 1 mm, time averaged axial velocity and droplet diameters

Droplet average size suggests a well homogenous population, with low dispersion of the different average values, and the presence of few larger droplets only in the spray tip.

Global average size results were also computed for five measurement locations close to the spray axis in a time window from 1 to 2 milliseconds, giving in this way an average drop diameter for the complete spray. Results are reported in fig. 6 for the three tested pressures. The graphic clearly report the effect of the pressure on to the droplet average diameter, which decreases for higher injection pressure. Data are consistent with other data sets reported in the literature, for example [6] measured 6.6 µm at 40 MPa and 5.3 µm at 60 MPa, with a similar trend even if the absolute values are different for the different experimental conditions and set-up.



| | 300 bar | 500 bar | 1000 bar |
|---|---|---|---|
| $D_{32}$ | 8.5 | 6.4 | 4.7 |
| $D_{30}$ | 7.0 | 5.4 | 4.0 |
| $D_{20}$ | 6.3 | 4.9 | 3.7 |
| $D_{10}$ | 5.6 | 4.5 | 3.3 |

**Fig. 6.** Measured average drop diameter in the spray, axial distance from the nozzle 50 mm (nozzle 6, 80 micron single hole).

## 5 Conclusion

Fuel sprays produced by different common rail injectors, with different nozzle hole diameter, were studied in condition of air and fuel pressures that are in the expected range of HCCI Diesel engine pre-injection. A large data-set of images allowed accurate measure of the spray penetration at different experimental conditions.

A common behavior for the tip penetration curve was found, with the velocity initially constant and then decreasing.

The effect of the air density is to shorten the length of the constant velocity path.

The constant velocity length is also linearly correlated to the nozzle diameter.

The velocity $V_0$ in the linear path is not predictable by the fuel rail pressure and a constant velocity coefficient, and requires to be measured for each injector-nozzle assembly and rail pressure.

Adimensionalization laws were found that correlate the penetration curve in all the experimental conditions, as a function of the velocity $V_0$, the nozzle diameter $D_0$ and of the air density. It was impossible to use the rail fuel pressure instead of $V_0$.

The size of the fuel droplets was measured by phase Doppler anemometry for the smallest nozzle diameter. Average result for the whole spray shows a strong decrease of droplet average diameters when fuel pressure increases.

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