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Setting up a PDPA system for measurements in a Diesel spray

L. Araneo¹ V. Soare² R. Payri², J. Shakal³

¹Politecnico di Milano, Dipartimento di Energetica, via La Masa 34, 20156 Milano Italy.

²CMT Motores Termicos, Universidad Politecnica de Valencia, Valencia, E-46022, Spain

³TSI Inc., 500 Cardigan Road, Shoreview, MN, 55126 USA.

E-mail: lucio.araneo@polimi.it

Abstract. A PDPA system was set up, optimised and used to measure the time resolved characteristics of the droplets inside a spray produced by a common-rail diesel fuel injection system. Some preliminary tests are performed with gas flows to optimise the optical set-up. Parametric studies are performed to gain an understanding of the particle density limits of the system, and their dependence on PDPA system parameters. Then the diesel spray produced by a single-hole injector is measured, with the fuel pressure ranging from 500 to 1300 bar, gas density in the test chamber ranging from ambient conditions to 40 kg/m³. Fuel and gas temperature were 25°C. Beam waist size is reduced to the minimum value allowed by the optical stand-off of the spray enclosure. Receiver lens focal length is similarly reduced. Receiver slit width, which is found to have a dramatic effect on the detection of droplets during the injection period, was tested in the range from 100µm to 25µm. Tests performed with two different slit heights are tested, respectively 1mm and 50 µm, show that this parameter has minimal effect on performance. PMT voltage (gain) is held to a moderately low value between 400 and 500 volt and the laser power between 400 and 800 mW in the green line. Optimum burst threshold is found to obtain the best quality data regardless of background level, which varies greatly in high-density pulsed sprays.

1. Introduction

The process of fuel injection and combustion in Diesel engines is crucial to obtain low pollutant emission levels together with high engine power and comfort performances, as it is required from a modern engine by law restrictions and market demands. For these purposes, a deeper knowledge of the spray characteristics is required, both for a better understanding of the fuel interaction with air and combustion and for more accurate CFD simulation of the fluid and thermo dynamic processes. Laser Doppler Velocimetry is a well-known and powerful technique able to measure the velocity and, under certain hypothesis, also the size of spherical particles like fuel droplets in the air. The application of Phase Doppler anemometry in a diesel spray is a quite challenging task because of the specific characteristics of a diesel spray. The pulsed injections in the time order of milliseconds require time-resolved measurements with microsecond accuracy. The maximum speed of droplets in the order of hundreds of meters per seconds, with very slow droplets in the spray periphery and in the opening and closing phases requires a very large dynamic range of measured velocity. The droplet size is also challenging to be measured, as with fuel pressure up to thousands of bar, it can range down to the minimum instrument sizing capability, in the order of the micron. Since Doppler measurements are possible only if one particle at a time is being measured, the high droplet concentration in the spray

core requires a very small measurement volume to avoid the multiple bursts. Optical access is often made difficult by the surrounding droplets that attenuate and deflect the incoming laser beams as well as the diffracted light signal, and thus signals originated from the smaller droplets could be very noisy or not at all visible. Consequently, there is a risk of biased average sizing towards larger droplet diameter. The necessity to measure the spray characteristics in an environment close to real injection conditions, namely gas high density and /or high temperature, requires for the use of a high-pressure test rig equipped with optical accesses. These are subjected to fouling and dirtying, and are another source of light distortion, eventually resulting in noisier signals.

Even in the presence of all these constraints, it will be shown that an accurate study and optimisation of the experimental set-up and of the operating parameters can lead to significant improvements of the results.

2. Experimental set-up

2.1. Injection System and test chamber

The injection test rig used is composed by a closed circuit with scavenging gas, where the fuel spray is injected, and optical access is provided through three perpendicular windows. The circuit can be kept open to atmospheric air, or closed and pressurized with air up to a density of 7 kg/m^3 , or pressurized by sulphur hexafluoride SF_6 up to 40 kg/m^3 , while keeping the pressure lower than the limit allowed by the system.

The spray is produced by a single-hole injector and is injected stream-wise in the gas flow; in this way window fouling is avoided and experiments can be run for many hours without the risk of signal degradation. An extended description of the set-up is given in [3], the injector used in these tests has a nozzle diameter of $110 \mu\text{m}$; fuel was provided at constant pressure from 500 to 1300 bar, and the pulse duration was selected between 1 and 4.5 ms; the injection repetition rate was 7 Hz, and in many tests measurements were stopped after 5 minutes, that is 2100 injections.

For preliminary PDPA set-up also a 4 mm diameter gas jet was used, while keeping the gas circuit at atmospheric conditions. The jet was generated by a TSI six-jet atomizer, and the oil seeding contained used for LDV measurements up to 100 m/s.

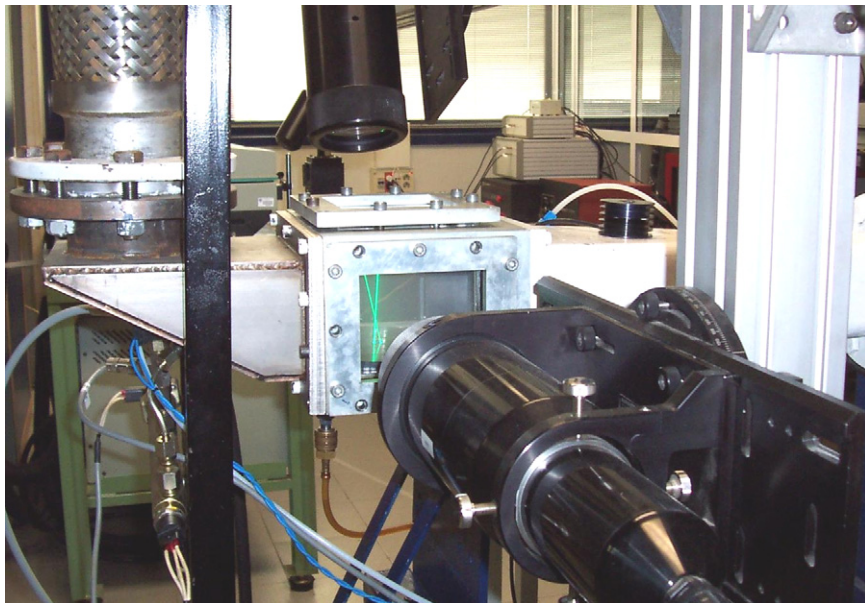


Figure 1: The set up, with the transmitting optic from the top, the receiving optic horizontal, the injector from the left in the scavenging flow.

2.2. Description of the PDPA system

The instrument used in this experiment is a TSI PDPA system, with a FSA4000 digital processor, already described in other papers [9]. For fully detailed explanation of PDA principles refer to a specialized book like [1]. The expected velocities to be measured in the spray [2] were up to 100 m/s, with droplet size up to few tens of microns, and high droplet concentration. The most important optical requirements are, then, a very small measurement volume with short fringe distance [7]. In this work the PDPA was consequently used with the following configuration:

- Laser: argon-ion, used on the green line (514.5 nm), for 1 component velocity and diameter measurement
- Bragg cell frequency (frequency shift) : 40 MHz
- Transmitting optic focal length: 200 mm
- Beam separation at the frontal lens: 57.6mm
- Beam diameter ($1/e^2$) at the frontal lens, after beam expander: 2 mm
- Fringe spacing: 1.8 μm
- Focused beam waist, nominal measurement volume diameter ($1/e^2$): 65 μm
- Receiving optic focal length: external 300 mm, internal for refocusing 250 mm
- Scattering angle: 70°
- Slit aperture: 100, 50, 25 μm (refocused on the measurement volume to +20%.)
- Velocity range: -36 ÷ 244 m/s (with maximum filter bandwidth 20-175 MHz, without down-mixing)
- Diameter range: up to 70 μm , with fuel refractive index 1.44

The main aim of our work was to understand the effect of many set-up parameters on the measurement results. After a preliminary choice of the optical configuration, we concentrated on some optical parameters and most of the software parameters to be chosen with the goal of optimizing the results, by taking into account mainly the acquisition data-rate and the measured velocity and diameter.

The available parameters and their main effect on the results were:

Laser power: when it is too low, small particles are not detected, but when it is too high, the largest particles can saturate the photomultiplier, the illuminated measurement volume becomes larger, increasing the background noise and the possibility that multiple scatter occurs. Used values spanned between 100 and 1000 mW at the laser source; each laser beam receives nearly 20% of this power in optimal conditions, the rest being lost in the transmission chain.

Windows material: a window is always a source of laser attenuation and distortion, and scratches on its surface or droplet deposited on it act like scattering sources affecting the coherence of the laser beam. We tested both plastic (methacrylate, 100x100 mm) and glass (borosilicate, Ilmadur, 80mm).

Slit width and height. The slit aperture cuts the view of the ellipsoidal volume formed by the two intersecting laser beams, so that a smaller slit width helps decreasing the measurement volume, which is useful when measuring inside a very dense spray. A too small slit, much smaller than the droplet to be measured, could lead to strong slit effect (also known as gaussian beam effect) [1]. An easy way to further decrease the measurement volume size is to use a pin hole, or two slits overlapping crossing at 90°, but this solution makes it impossible to determine the effective measurement volume dimension. We tested slits of 100, 50 and 25 microns, and the intersection of the 25 and 50 ones.

Photo-multiplier voltage (gain). Its effect is similar to that of the laser power, with different relative values because the amplification chain is not linear.

Burst threshold. It affects the detection of the burst. Generally it has a value that maximizes the data rate. A higher value excludes the smaller signals, i.e. the smaller particles, biasing the average results. A very low value increases the detection of noise. In a very dense environment it also happens that the background noise, caused by light scattered by droplets on the receiving optical path illuminated, becomes very strong. If the threshold is too low, the signal never goes below it and many bursts or even one full injection are seen as a unique, long incoherent signal, so no droplets are detected. The threshold values spanned between 30 and 200 mV.

Signal to noise ratio threshold. It is used to reject noisy signals, but if set to very restrictive values it results in rejection of small particles, more evident in a dens region where all signals are more noisy. The available values are “High, Medium, Low, Very Low”.

A four channel digital oscilloscope was used to monitor the different signals: photo-multiplier raw signal, burst (pedestal removed), acquisition gate (the processor has recognized a possible burst and is performing FFT analysis), and, when available, the injector trigger. The BNC cables were accurately cut at the same length to avoid phase shifting when comparing the bursts issued by the three photo-multipliers, since at 80 MHz a cable difference of 1 centimeter introduces a phase difference of 1 deg.

It is useful to describe the signal processing performed by the TSI system. The scattered light signal is collected by three photomultipliers, where it is amplified by a selectable high voltage (gain). The electric signal is then analogically high-pass filtered (20 MHz) to remove the pedestal. Signal filtering and down-mixing can be selected to reduce the noise and the bandwidth required by the FFT process. Burst detection is performed, with a variable threshold and other frequency analysis criteria. Noisy signal can be rejected on the basis of the SNR level. Finally, spherical validation can be performed, and a criterion of diameter-signal amplitude can be applied.

3. System optimisation

3.1. Preliminary optical set-up

Extreme care was taken previous to any experiment in setting up the optic properly. The laser mirror and diaphragm were correctly aligned and cleaned, as well as the Bragg cell and all the optics used to manipulate the laser beams and deliver them properly polarized to form the measurement volume. Beam parallelism was checked before mounting the front lens, and beam crossing was improved by using both a pin-hole and a microscope objective [8]. The receiving optic was aligned onto the beam intersection while keeping the windows on place and, when necessary, with the test rig pressurized, to compensate for the possible light deflection caused by the window deformation when internal pressure is applied. It was found that an incorrect alignment, in the order of the tenth of millimeter and hence not perceivable by the eye, can decrease the data rate down to 30% of its maximum value. The optimal alignment was found and defined as the position where the data rate registers a maximum when taken in steady conditions, like in a continuous gas jet, and all the other operative parameters are kept constant. To operate in a fast and efficient way, the laser power was tuned to reach a data rate in the order of 1000 droplets pr second, and the gas jet at few meters per second of speed.

3.2. LDV set-up in steady conditions, choice of signal filters

The steady gas jet in ambient air, without any window on the optical path, was also used to understand and optimize the frequency filters used onto the signal before the AD conversion and FFT analysis, and to estimate the error committed in the velocity measurement. A set of tests was done with the steady gas jet at different velocities (the 1 and 10 m/s are reported here), and many combinations of band-pass filters and down-mix frequencies were used.

Figure 2 reports the results of the RMS velocity obtained for the above-mentioned gas jet velocities. As expected, the RMS is lower for narrow bandwidth filters in combination with strong down-mixing, which is applied to reduce the 40 MHz frequency added by the Bragg cell. For the use with diesel spray, with velocity up to 100 m/s the larger filters must be used, and down-mixing is no more possible. The available filters are then the 40-120 MHz, which has the defect of excluding negative velocities, and the 10-100 MHz, which has a reduced maximum velocity but can measure negative values, and will be used in the external region of the spray, where the turbulence can generate reversed flows.

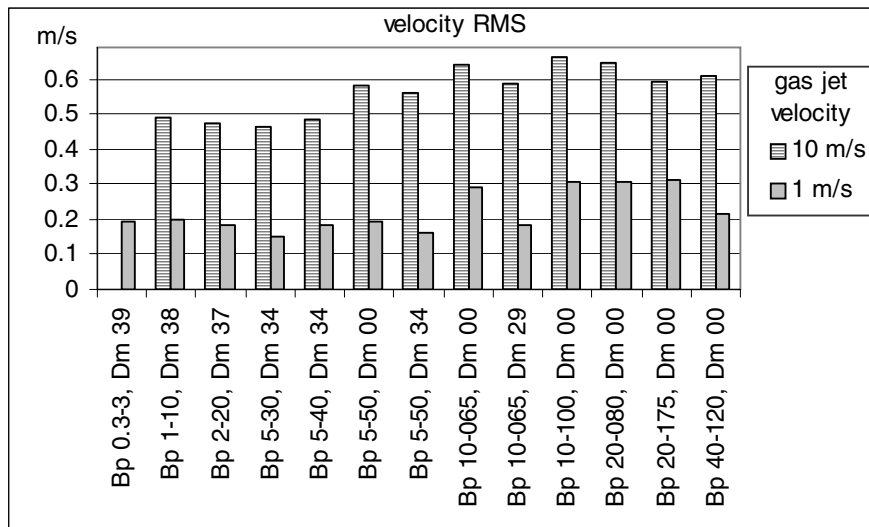


Figure 2: RMS for two different steady gas jet velocities, and different band-pass filters and down-mix frequencies. Key: Bp 1-10 Dm38 = Band-pass 1-10 MHz, Down-mix 38 MHz.

3.3. PDA set-up in steady conditions, effect of windows

To test the effect of the windows presence, data were acquired with different configuration: without windows, with a window on the transmitting side, on the receiving side or on both, and changing the material of one window (methacrylate and borosilicate). Each time the system was re-aligned, by looking as usual for the maximum data rate, because the window thickness shortens the distance between the lens and the focusing point. For each configuration different tests were performed, to take into account the variability of results caused by the re-alignment and the possible variation of efficiency in the measurement chain. The plastic windows showed to preserve the data rate more than the glass ones, so for the remaining pressurized tests the plastic windows were used.

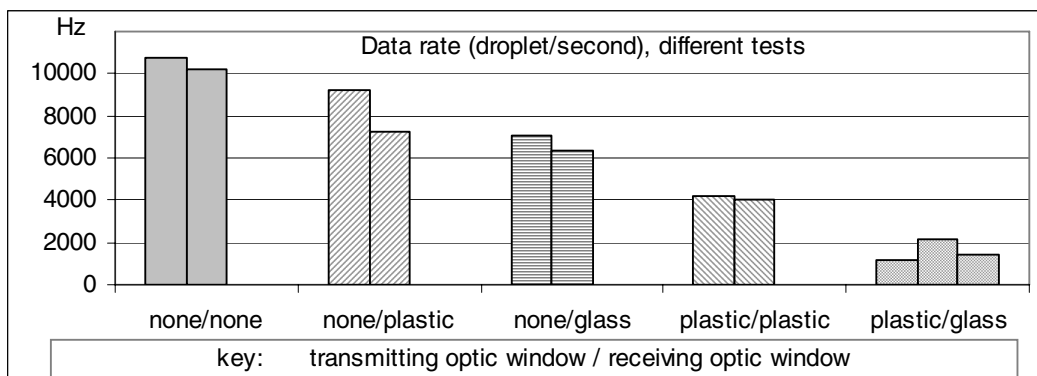


Figure 3: acquisition data rate for different combination of windows at the transmitting and receiving optics. Different tests are taken at each combination.

3.4. PDA measurements in a diesel spray

The measurements performed in a diesel spray have the typical behavior shown in the following figure 4, where it is reported the velocity of droplet as a function of the time, measured near the spray axis at a distance of 40 mm from the nozzle. Many injections are superimposed, synchronized by the trigger, to obtain sufficient data to describe them. The delay from the trigger to the first droplet is caused by the mechanic injector delay plus the convection time required for the droplets to reach the measurement location. The first burst of slower droplets is typical for the spray tip, followed by a

quasi-steady period of the injection, and then by the trailing edge of the spray, caused by the injector closing. Generally the quasi-steady period is the most difficult to measure because of the high droplet concentration. The quality of the results corresponding to this phase of the injection can be compared to the ones from the trailing edge, which is much easier to be measured, and as such is the best reference for good measurements.

In the external region of the spray the quasi-steady phase is characterized by lower velocities, and measurements are much easier if the dense core of the spray can be avoided [2]. Consequently, if steps forward are to be made with the PDPA technique in Diesel sprays, then the objective has to be to optimize the results in the difficult central region of the spray, during the quasi steady part of the injection.

3.5. Choice of the slit width

Different slits were tested to check their effect on the quality of the results. Figure 4 shows the velocity results, obtained in a location close to the spray axis. For each test the acquisition was stopped after 10000 droplets had been collected; if the quasi steady region is badly defined it means that for that particular set-up it was difficult to be measured, and results are preferentially filled by the trailing edge droplets, which are always easy to detect. It is evident the dramatic improvement of the results when passing from the 100 μm slit to the 50 μm one, and still a marginal improvement is obtained with the 25 μm slit. In other more difficult positions the 25 μm slit showed further improvements, so it was kept for the remaining part of the work. A test with a reduced slit height, obtained by crossing the 25 μm slit with the 50 μm one at 90°, did not show any evident improvement, it was very difficult to align, and it was preventing the evaluation of the measurement volume dimension generally performed in data post-processing, so it was no more used.

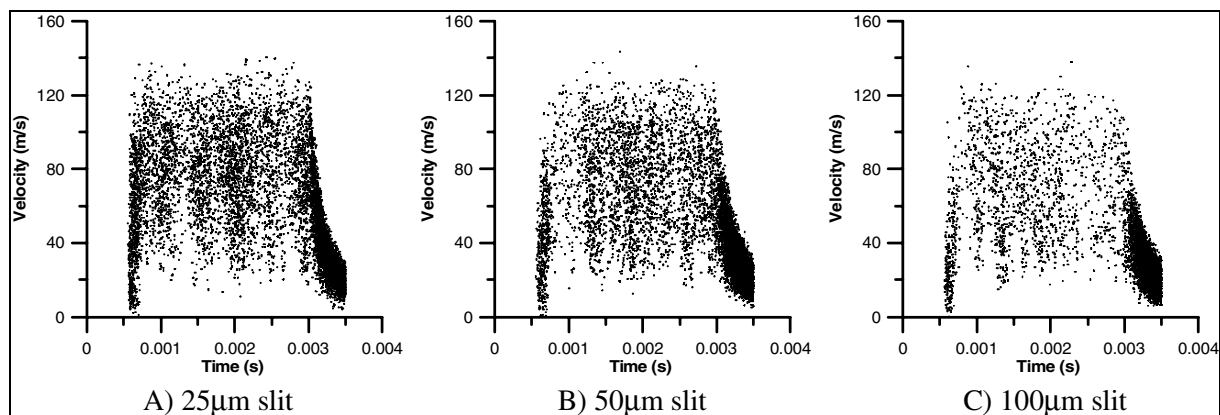


Fig 4. Influence of the slit aperture at the receiving optic: velocity results 40mm downstream from the orifice, 1mm off-axis, $P_{inj}=500\text{bar}$, $P_{amb}=7\text{bar}$ (air), injection electronic pulse 2 ms

3.6. Control of acquisition quality

During data acquisition, a wide set of graphic plots were always displayed during the acquisitions to check the data quality.

The velocity and frequency histograms are used to verify that the velocity range limits are not reached; also isolated peaks at given frequencies often indicate that noise is being detected. This noise also appears in the time encoded data as a narrow stripe of velocity data (Figure 5 A), whose frequency is often close to a finite multiples of the Bragg cell (40, 80, 120 MHz), combined together with the down-mix frequency when applied.

The diameter vs. time chart provides information on the size evolution during the injection (figure 5B), showing generally larger droplet in the transient phase of the injection, when the nozzle is partially closed by the needle and atomization is less efficient, but this kind of charts can not help in understanding if results are good, or, on the contrary, if noisy signals are being detected

The phase AB-phase AC scatter plots (figure 5C) give many information: if too many droplets are far from the sphericity ideal line, this indicates the presence of non-spherical droplets, or again too much noise. Spherical droplets all laying on one side of the sphericity line generally indicate a bad calibration of the photomultipliers, more rarely a problem of incorrect beam polarization. When measurements are very difficult because of high spray density, the noise becomes stronger than the smallest droplets, which then shows a high phase random scatter. It can also occur that many small droplets, close to the lower size limit, are then seen as large droplets close to the maximum size limit. Such droplets are generally discarded later by applying the size-intensity validation criterion.

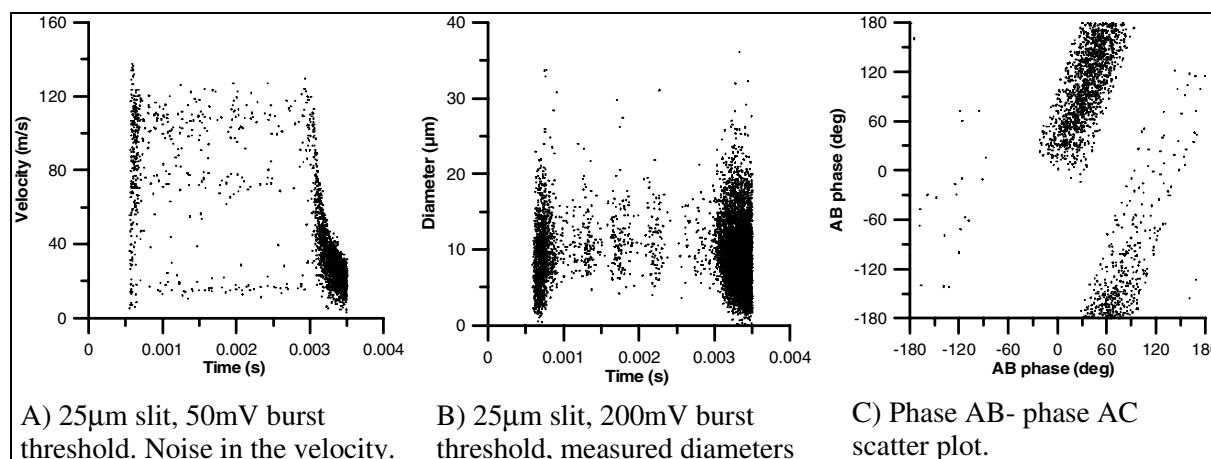


Fig 5: Other plots available during acquisition and showing some of the available results

3.7. Effect of the laser power, burst threshold, PMT voltage, SNR

The effects of these three parameters are strictly connected, so a full set of experiments was performed in a location 0.7 mm away from the spray axis (in the direction that brings the laser path outside the spray core), at 40 mm from the tip in axial direction; fuel pressure was 800 bar and gas density 14 kg/m³. The parameter values used are:

- Laser power: 400, 600 and 800 mW
- PMT voltage: 400 and 450
- Burst threshold: 50, 100 150 200 mV
- SNR: Very Low and Medium

Only 40 of the 48 combinations were tested, since the combinations of the lowest laser power and PMT voltage resulted in very low data rate and were thus immediately excluded. In each test 10000 droplets were collected, or the acquisition was stopped after 5 minutes (2100 injections) if the data rate was too low. Many conclusions could be drawn afterwards, some of them quite obvious, others more unusual and unexpected. The results are well summarized in figure 6, where the data rate and the average mathematical and Sauter diameter (D_{10} and D_{32} , averaged over the whole injection time) are reported for the 40 tests.

An increase of the data rate generally means better acquisition, unless too much noise is validated as droplets, but this can be better seen in the time resolved velocity results (figures 4 and 5). A smaller D_{10} is generally linked to higher data rate, but again, it gives no information on the presence of noise. The Sauter diameter D_{32} follows the same trend of D_{10} unless noise is present, in this case the D_{32} can strongly increase. That is for example the case of $BT = 50$ and 100 mV, where noisy signals appear with random diameter, some of them very large so that D_{32} is strongly increased. The combination of these three data can be used as a good mark for setting up the system: increase of data rate and decrease of D_{10} and D_{32} are an improvement; increase of data rate and D_{32} with D_{10} decreasing means generally that noise is validated. The result of higher SNR (medium instead of very low) is generally a rejection of noise and smaller droplets, resulting in cleaner velocity profiles, but lower data rate and

higher average diameter. It is also important to note that the measured average diameter D_{10} ranges here from 10 to 12 microns, meaning a 20% variation due to solely the instrument settings.

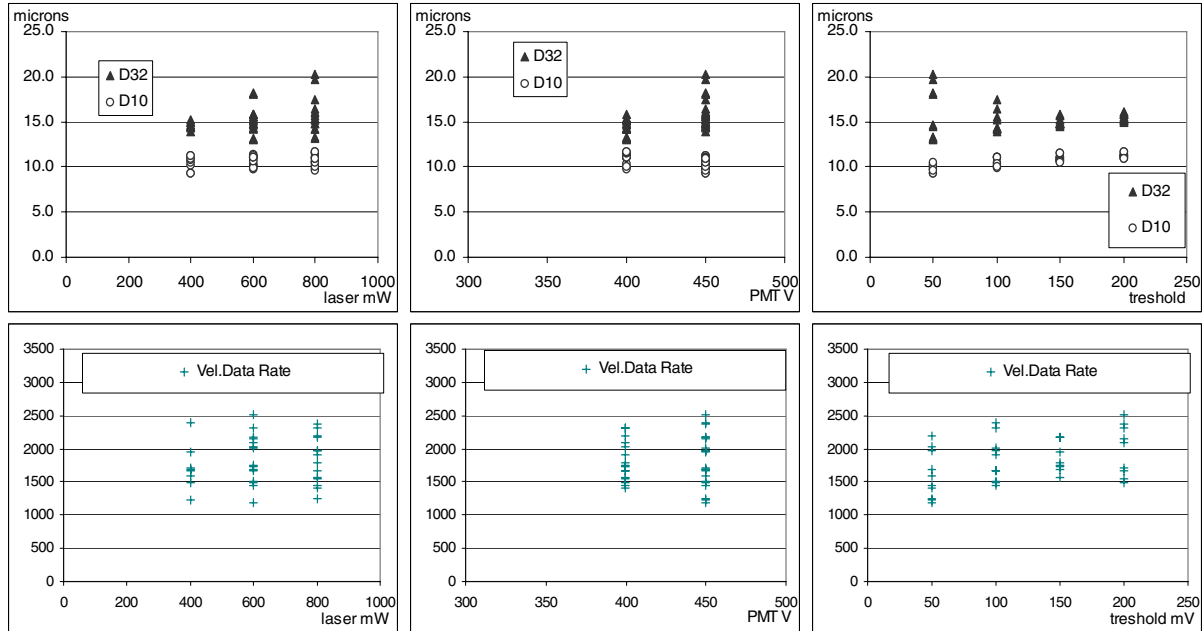


Fig 6: Average diameter and data rate for the tested conditions. Fuel pressure 800 bar, gas density 14 kg/m³, location at 40 m from the spray tip, 0.7 mm off axis.

3.8. Example of velocity and size results

As a final example of the results, the profiles of velocity, size and data rate are measured with a restricted set of four optimized set-up conditions, at different locations throughout the spray. The graphs reported in the figure 7 show the average profiles obtained at 40 mm from the nozzle tip, moving the measuring point across the spray, along a diameter at -45° in the scattering plane respect to the laser beams direction, being 70° the position of the receiver. The negative axis values correspond to the side where the incident and the scattered light cross the spray with the shortest path. The averages are obtained on data from the spray tip and its quasi-steady part, by making the injection pulse longer than the acquisition window, which was 5 ms, so that the trailing edge is avoided.

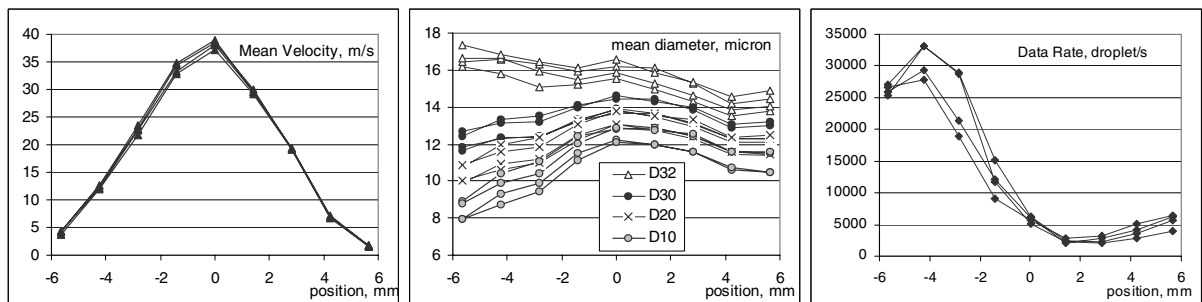


Fig 7: Velocity, size and data rate average profiles across the spray, trailing edge excluded. Gas density 40 kg/m³, fuel pressure 800 bar, distance from the nozzle tip 40 mm. Set up conditions: laser power 600 and 800 mW, photomultiplier voltage 450 V, burst detection threshold 100 and 150 mV.

The results show that the measured velocity is nearly independent from the set-up parameters. The data rate shows a weak dependence on the set-up parameters, and a strong dependence on the

measurement location in the spray: inside the spray goes down to nearly 10% of the value measured in the external parts, where the optic path is less disturbed by the dense core region. The measured diameters shows the same scatter already reported in the previous paragraphs, and gives an idea of the confidence that should be attributed to this kind of measurements.

4. Conclusions

A PDPA system from TSI was set-up to measure the droplet size and velocity in a diesel spray. A parametric study of many set-up parameters showed their influence on the acquisition results.

A very narrow slit aperture, in our case the smallest available that was 25 microns, is necessary to see inside the denser part of the spray. Laser power in the range of 400-800mW, photomultiplier amplification voltage in the range of 400-500V and burst detection threshold of 100-200 mV were combined in order to find their optimum values leading to an increased data rate. This is almost always an indication of better results, with the limitation that beyond a certain level noise will also be detected and validated.

Some criteria to recognize bad measurement results are given. Velocity results are only slightly affected by set-up and can be considered very reliable, while diameter results always show dependence on the set-up, with variation in the order of $\pm 10\%$ in optimal conditions. The decreasing data rate inside the spray suggests that only a small percentage of the total of droplets is detected and measured.

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