

Assessment of Pulsed Gasoline Fuel Sprays by Means of Qualitative and Quantitative Laser-based Diagnostic Methods

by

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Abstract

The combination of qualitative measuring techniques such as imaging, with quantitative drop sizing techniques like Laser Diffraction and Phase Doppler Anemometry (PDA), has been applied for assessing the sprays formed by injectors for gasoline direct injection (DI) engines.

Both, the sizing instruments as well as the imaging, are offering temporal resolution in order to investigate the important features of pulsed DI sprays. Using a combination of the spatially integrating Laser Diffraction instrument with strobe illuminated dual view 2D-imaging, the overall spray properties have been assessed. Having the 2D information of the global spray shape in two perpendicular directions allows to immediately correlate the concentration and drop size measurement results of the Laser Diffraction instrument with the global spray appearance. Thus, the changes of the spray pattern can be related with the sizing information as the spray propagates away from the injector.

For injector design improvements, however, it is required to achieve a higher spatial resolution and especially to measure closer to the injector exit orifice than the Laser Diffraction allows. By using a Phase Doppler Anemometer, the different phases of the injection event, i.e. opening of the injector, main spray and closing phase of the injector, can be distinguished from each other. However, in sprays, where the spray geometry is changing with time, the Phase Doppler instrument can suffer from its high spatial resolution, yielding to results, which are difficult to interpret.

Assisting the PDA with a simultaneous imaging technique of similar spatial resolution creates a very robust experimental approach. By visualizing the plane perpendicular to the PDA probe volume, i. e. the crossing of the PDA laser beams on the spray image itself, a very precise adjustment of the PDA probe volume in regard to the spray rather than the nozzle can be achieved. This becomes critical when getting to the near orifice area at distances closer than 10mm. The synchronized images also bring additional information to the point measurement provided by the PDA. It becomes easier to choose which particular phase of the spray formation the user wants to characterize. Finally, more confidence into the interpretation of PDA data from locations close to the injector tip is reached.

Introduction

Typically, DIG sprays are generated by pressure-swirl type injectors and are emerging into an environment where pressure and temperature change during the spray propagation. Depending on engine speed, the time left for vaporization is rather limited, driving the need for small droplet sizes, as well as a consistent and repeatable spray quality from one injection event to the next.

The complex 3D and time-dependent nature of DIG sprays generated with injection durations of the order of 1 ms, cannot be fully resolved by the available instrumentation, especially when larger sample numbers have to be measured. Resulting from the inherent constraints of the measurement devices, the mentioned spray properties can only be obtained by applying a certain degree of either temporal or spatial averaging.

The approach of describing a spray by spatially and/or temporally averaged data may be sufficient for initial spray assessment, however, from an injector design point of view, temporally resolved data from within one pulse have to be obtained. Only by capturing the transient nature of the spray, the start and end phases of the injection event can be assessed, finally leading to injector design improvements.

The scope of this paper is to reveal the practical use of the different instruments and their relative combinations applied to the investigation of DI injector sprays in a product development environment. This means to bridge the gap between research like studies on single injectors and the fast characterization of a number of parts, which will further proceed to engine testing. Since both goals are requiring different measurement strategies, different combinations of instruments for optical spray assessment have been applied for reaching either one of the goals, finally leading to a faster and more thorough understanding of the sprays.

However, it is not intended to compare the results of the different sizing instruments directly, since either one has its specific merits and shortcomings, which have been addressed in earlier papers, such as Dodge et al., 1987.

Spatially integrated measurement: Laser Diffraction / Imaging combination

When starting with spray investigations of a new injector design, the first approach is done by running the injector at atmospheric ambient conditions using a combination of integral methods, which are applied subsequently. Here, these are single shot imaging using strobe light illumination and laser diffraction droplet sizing.

Laser Diffraction

For laser diffraction droplet sizing, an Insitec/Malvern Spraytec™ instrument is applied. It uses an expanded laser beam passing through the spray. Each particle illuminated by this beam contributes to the light intensity recorded by the receiver. From the light intensity distribution captured by the receiver, a particle size distribution is calculated, as though the particles were spherical (cf. Harvill and Holve, 1998; ISO 13320-1:1999(E)).

This ensemble measurement technique is a concentration-based measurement, where the particle velocities are not accounted for. Therefore it is preferred to measure at locations where the velocities of droplets of different sizes have reached a similar level. Moreover, the laser diffraction technique needs a high enough concentration of particles in order to obtain a statistical viable measurement. On the other hand having too many droplets in the measurement volume may lead to multiple scattering effects which affect the accuracy as well. Therefore a measurement location of 50 mm downstream of the injector tip through the spray center is selected. A beam diameter of 15 mm is used for the measurements, which means that the measurement is spatially integrated within a cylinder of 15 mm diameter and crossing the spray through a horizontal diameter. The sampling rate is set at 2500 Hz which is the maximum data rate of the instrument, leading to one size distribution every 400 ns. The receiver focal length is set at 100 mm, which gives a measurable size range from 2 to 230 microns. In order to avoid the vignetting effect (c.f. ISO 13320-1:1999(E)), the injector is positioned as close as possible to the receiver. Thanks to a purge system using compressed air, an air flow is created on the front surface of the lens and avoids that droplets get deposited on the optic. With the spray investigated, a distance of 80 mm from injector axis to the front lens, has been set and checked against vignetting.

Single shot imaging

In general, the single shot imaging technique is used for obtaining geometrical information from the investigated sprays. For this, the spray is briefly illuminated by a strobe light of around 10 μs duration. This is still short enough in order to obtain a quasi frozen image of the spray. The integral illumination provided by the strobe is preferred to a light sheet since the entire spray can be captured rather than cutting just a slice through it. The resulting images are

captured by a CCD camera (12 bit resolution, 1024x1280 pixels, 10 μ s exposure time, Flowmaster™ from LaVision). From subsequent analysis, the spray penetration and the spray angle can be determined for various timings. By combining two simultaneously synchronized gated cameras set at 90 degrees from each other, the method reveals the integral appearance of the spray as 2D images in two perpendicular directions. This approach of using a dual camera system is necessary especially when testing parts which present a particularly strong in-homogeneity of the spray pattern, as will be shown in the following. Generally thirty consecutive pulses are recorded at a chosen fixed delay time with respect to the injector trigger signal. An averaged image and a standard deviation image is recorded in order to check for the pulse to pulse repeatability of the spray. From the resulting images, the spray penetration and the spray angle can be determined for various timings. In order to visualize the interaction of the laser diffraction probe volume with the spray, figure 1 shows typical imaging results from a non-symmetric spray with the overlaid Laser Diffraction probe volume.

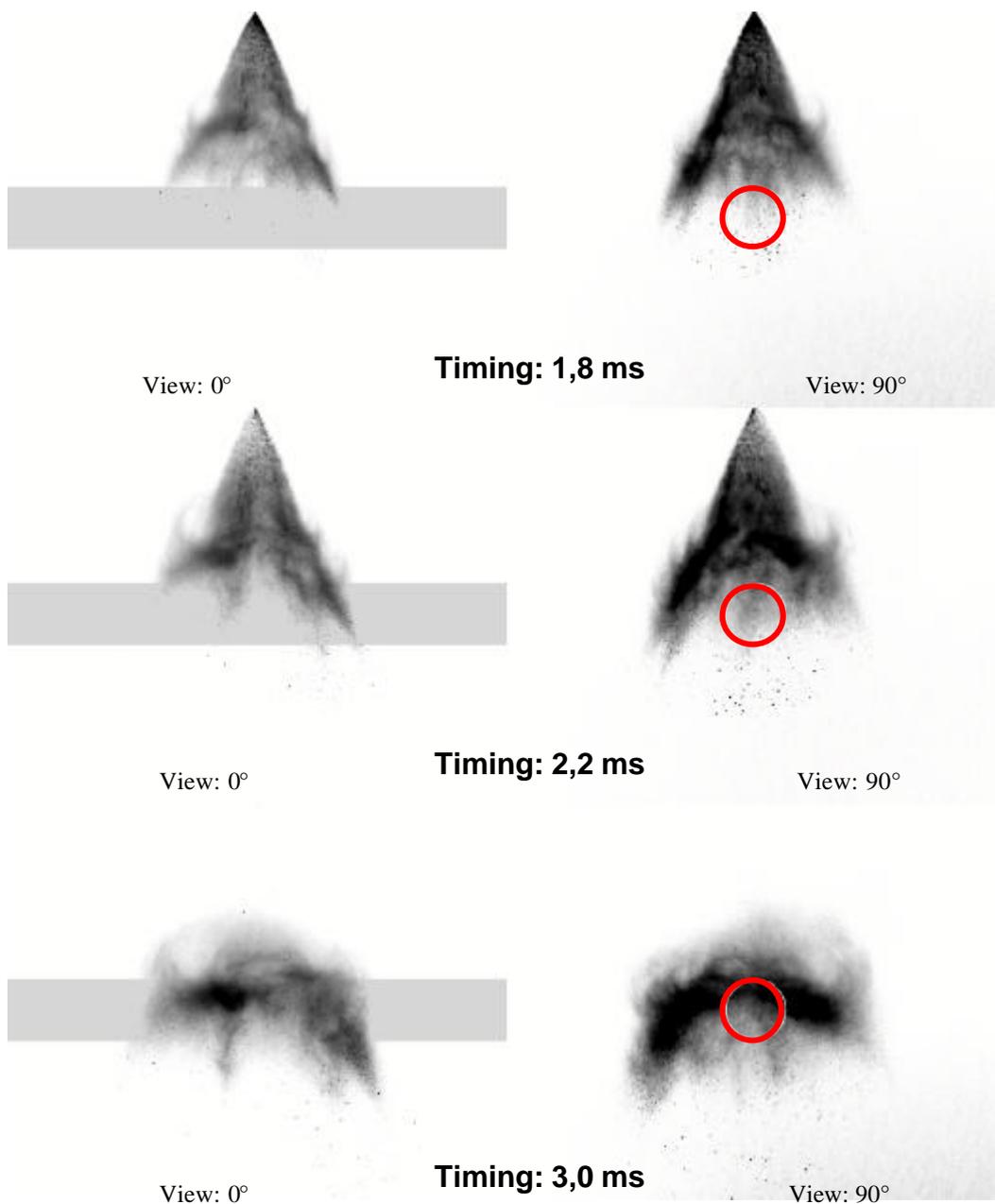


Figure 1: Images resulting from single shot imaging including the location of the laser diffraction probe volume

Time resolved measurements

The injector tested here is a pressure swirl inwardly opening injector designed for wall-guided DI combustion. The test fluid is indolene, pressurized at 70 bar and the pulse duration is set at 1.5 ms. The tests are done at atmospheric ambient conditions. Individual images are shown in Figure 1, which reveal more details than the smoothed averaged images over thirty cycles. The images are shown at three different timings and from the two directions, and a representation of the laser diffraction probe volume is superimposed to them.

Figure 2 shows a representation of the laser diffraction time resolved measurement over one entire injection cycle. The acquisition is set to automatically start when the transmission falls under 98% or when the scattered signal level on the detector reaches a certain threshold set by the user. Here the acquisition started at 1.8 ms, when the front edge of the spray enters the measurement volume as seen on figure 1. The instantaneous volumetric characteristic diameters (D_{V10} , D_{V50} and D_{V90}) are represented versus delay time as well as the optical transmission and the volumetric liquid concentration. Two corresponding size distributions are shown above the time resolved graph, one at 1.8 ms when the front edge of the spray enters the laser beam, the second one at 3 ms which corresponds to the highest density of the spray according to the laser diffraction beam attenuation. Since the optical transmission goes down to about 15%, the instrument manufacturer's multiple scattering correction algorithm is applied for the data deconvolution.

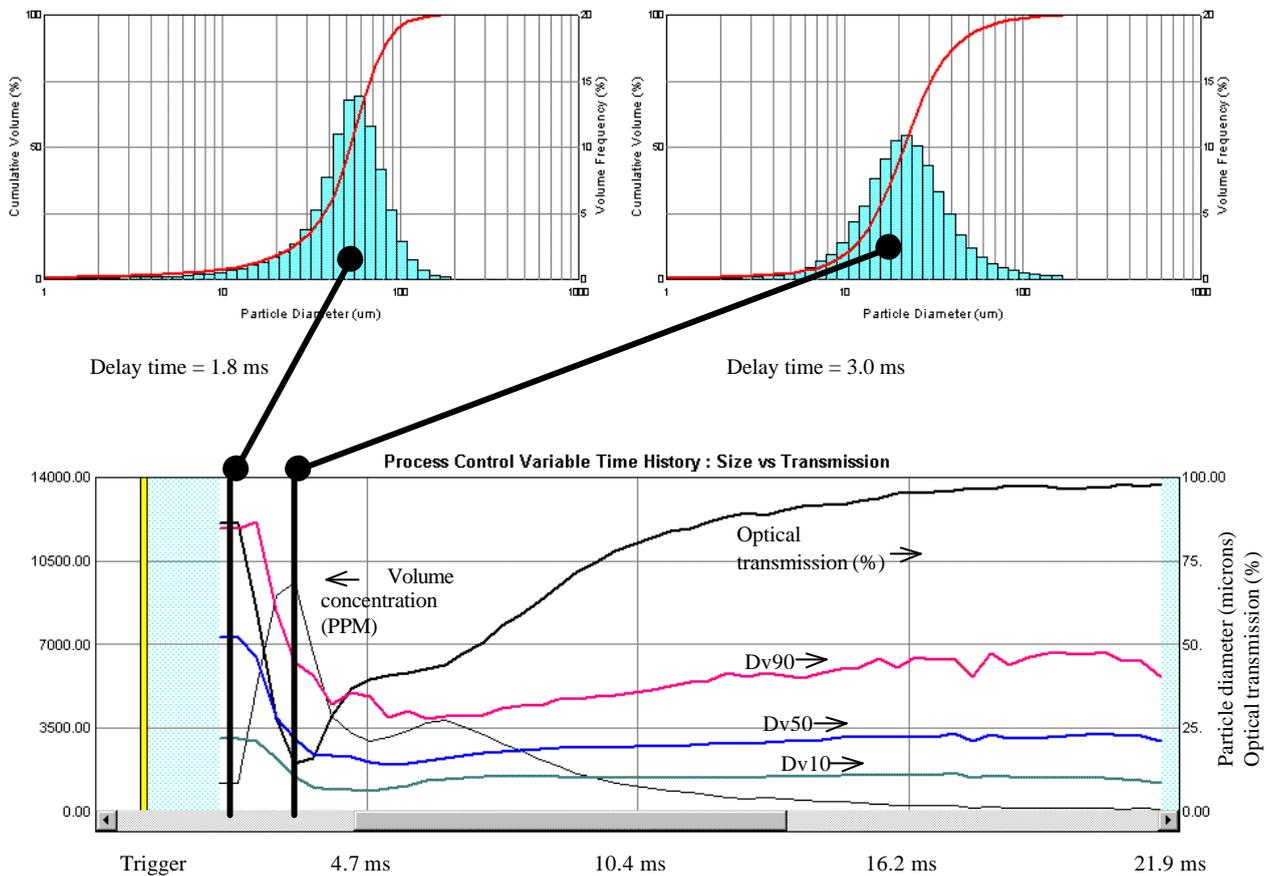


Figure 2: Temporal evolution of one injection cycle measured with the laser diffraction

Figure 1 clearly indicates which part of the spray is captured by the laser diffraction instrument at a certain time. At 1.8 ms, it shows the presence of big drops created during the opening phase of the injector, and typically referred to as sac volume spray. This is confirmed by the high value of particle sizes measured at this delay time. It is important to use two cameras at 90 degrees from each other, in order to determine which part of the spray is within the measurement volume of the instrument. The dual-image shows that the laser diffraction is not catching the initial spray front since it is non-symmetric on this particular injector. By turning the nozzle 45 degrees around its axis, the laser

diffraction would probably start the acquisition a little bit earlier. This is probably not affecting the droplet sizing information, on the other hand it shows that the laser diffraction instrument cannot be used to measure spray penetration.

At 2.2 ms the characteristic diameters of the volume distribution (D_{V90} , D_{V50} , D_{V10}) as measured by the laser diffraction decrease. The images show that the spray volume has almost completely left the laser beam and that the instrument is now catching the main part of the spray. At 3 ms, the images confirm that this timing corresponds to the densest part of the spray present in the probe volume. The laser diffraction measures much smaller particle sizes at this delay time. After 3 ms, the D_{V90} , D_{V50} and D_{V10} continue to decrease, which is probably due to big droplets leaving the probe volume due to their inertia as the small ones tend to stay longer in the laser beam. Afterwards the mean sizes increase very slowly, which could be attributed to evaporation effects. These results are very similar to what was observed by Le Coz, 1998.

It is very important to keep in mind that the laser diffraction is a concentration based measurement and therefore will account more for the particles that are moving slower in regards to the fast ones. With a 15 mm laser beam diameter this effect can become very important especially for the tail of the spray.

With the current maximum data acquisition frequency of the instrument (2.5 KHz), only four size distributions can be measured between 1.8 ms and 3 ms. However the images show significant changes of the spray pattern during this period. This creates the need for a higher data rate in order to better resolve the time span between the front edge and the densest part of the spray. It is planned for the future to upgrade the instrument to a 10 KHz data acquisition rate.

Time integrated measurements

The value of generating spatially integrated and time resolved data within one cycle has been shown. But in order to have a rapid and repetitive evaluation of the atomization performance of a large number of injectors, it becomes necessary to integrate the result in space and time. This is especially important if cycle to cycle and part to part variations need to be quantified. To achieve this, the scattered light onto the detector is integrated over one entire injection cycle, and the scatter plot is then transformed into a size distribution. The integration duration of the detector is set at 96 ms with an injection repetition rate set at 10 Hz (100 ms period), therefore this temporal integration corresponds to 96% of the injection cycle. This way, one size distribution is obtained for each injection cycle. This measurement is done on 100 consecutive injection pulses. Averaged mean diameters and standard deviations are then computed.

Spatially and Time resolved measurements: Phase Doppler / Imaging combination

The droplet sizing data taken at 50 mm below the injector tip results from the interaction of the atomization performance of the investigated injector, with the transport processes which take place while the spray propagates away from the injector. In order to distinguish between the injector design related effects on the spray and the transport processes, it becomes necessary to retrieve time resolved data from a position much closer to the injector tip. This is achieved by using a Phase Doppler Anemometer (PDA) in conjunction with a laser light sheet imaging technique.

Phase Doppler Anemometry

The 2D Phase Doppler Anemometer measures simultaneously the size, two components of the velocity and the arrival time of individual droplets passing through a very small probe volume created by the intersection of four laser beams. Due to the intermittent nature of the spray and the small size of the probe volume, one injection event does not create a significant amount of data, therefore several injection cycles (on the order of several hundreds) have to be accumulated to create one valid measurement. This can only be done if the spray is proven to be repetitive, which has been checked with the single shot images and quantified with the laser diffraction technique previously. Since for each droplet measured by the Phase Doppler, its arrival time after start of injection is recorded, the whole injection event can be reconstructed from the accumulation of several cycles. The result can be shown as a scatter plot where each point represents a droplet velocity or size versus delay time as shown on figure 5.

The instrument used is a TSI/Aerometrics two components Phase Doppler Particle Analyzer, with a processor Aerometrics RSA 3200. Three different optical configurations have been applied in order to test the effect of the probe volume size in dense spray areas. The optical configurations are given in table 1. The index of refraction is 1.39, and the off-axis angle of the receiver is set at 30 degrees forward scatter.

With this instrument the size and velocity measurement channels are independent and can be combined via the software after the data acquisition is done in order to get the velocity/size correlation. The size measurement of the Phase Doppler is more restrictive than the velocity measurement, as the Doppler signals have to pass through more validation criteria such as droplet sphericity check, multiple particles in the probe volume, longer transit time needed for processing...etc (for reference c.f. Bachalo, 1993, 1999; McDonell and Samuelsen, 1988). On the other side, when doing pure velocity measurement, the instrument is able to catch any liquid element regardless of its shape. The ability to measure separately the velocities alone and the velocity plus size is very useful when getting close to the injector orifice where not all the droplets are spherical. In the following, it will be referred to 1D-LDV, 2D-LDV and 1D-PDA for respectively pure axial velocity measurements, axial and radial velocity measurements, and droplets axial velocity and size measurements.

Table 1: PDA optical settings

Optical configuration #	C4		C5		C6	
	Ch1 Axial vel & diameter	Ch2 Radial vel	Ch1 Axial vel & diameter	Ch2 Radial vel	Ch1 Axial vel & diameter	Ch2 Radial vel
Wavelength (nm)	514.5	488	514.5	488	514.5	488
Transmitter front focal length (mm)	250	250	500	500	500	500
Beam expander	1	1	1.43	1.43	1	1
Beam separation (mm)	40	40	57.2	57.2	40	40
Beam waist (microns)	117	111	164	155	234	222
Interfringe (microns)	3.23	3.06	4.5	4.3	6.44	6.1
Velocity range (m/s)	-64→116	-61→61	-90→162	-85→85	-129→232	-122→122
Receiver front focal length (mm)	500		300		300	
Receiver clear aperture (mm)	72		72		72	
Slit (microns)	100		100		100	
Max Diameter (microns)	132		110		158	

The goal while using this instrument is to get reliable size and velocity information in a “known” part of the spray and as close as possible to the injector orifice. Getting data close to the orifice has two main interests: one is to be able to better separate the different phases of the injection cycle in terms of atomization quality and further on improve the injector design; the other one is to provide a correlated velocity size probability density function as initial condition to the Computational Fluid Dynamics for combustion simulation.

Typical DI injectors produce hollow cone sprays, where the main part of the liquid is concentrated within a thin sheet. In order to characterize this liquid sheet for a specific injector, data were taken at 5 mm below the tip. It was found that in this particular region of the spray, the Phase Doppler could barely measure anything during the injection duration. The PDA gave results during the initial phase of injection and during the tail, but it seemed to be blind during the main part of the spray. However, a quick check of the PDA raw signals on an oscilloscope confirmed the presence of particles during the entire spray event. Moving the probe volume just a few hundred microns away from the injector axis brought back a good data rate on the PDA also during the main spray event. Based on this observation, it was decided to add a simultaneous light sheet imaging technique to the PDA measurements. From this, the PDA probe volume location with respect to the spray could be determined with high accuracy.

Laser Sheet Imaging

A 12 bit resolution, 1024x1260 pixels, 10 microseconds gated Flowmaster™ camera from LaVision is set-up, together with a frequency doubled Nd:YAG laser (532 nm wavelength) from Big Sky Laser. The laser pulse duration is selected around 10 ns and the pulse energy set around 10 mJ. A set of optics with an adjustable slit mask is used to create a light sheet of about 300 microns thin. The camera field of view is about 13 mm high by 10 mm wide.

The experimental setup is represented in figure 3. The PDA transmitter and receiver are positioned so that the optical path crossing the dense part of the spray is minimized. The transmitter is facing the camera on the same axis. The light sheet is perpendicular to the common optical axis of the camera and the PDA transmitter, and contains the vertical axis of the injector as well as the PDA probe volume. To achieve this, the PDA receiver is first of all adjusted on the probe volume by the use of a humidifier. Then a thin piece of paper is positioned in the cross-over point of the PDA beams by visualizing the spot on the slit of the receiver. Finally, the light sheet position and thickness is adjusted to overlap the PDA probe volume by visualizing them on the paper (eventually with the help of the receiver slit). The injector is mounted on a 3 axis traverse system, so that the spray can be positioned as desired around the measurement volume.

From this setup it is now possible to visualize the crossing of the four PDA beams with the camera, as they intersect with the spray, together with a synchronized laser sheet view of the spray at any delay time.

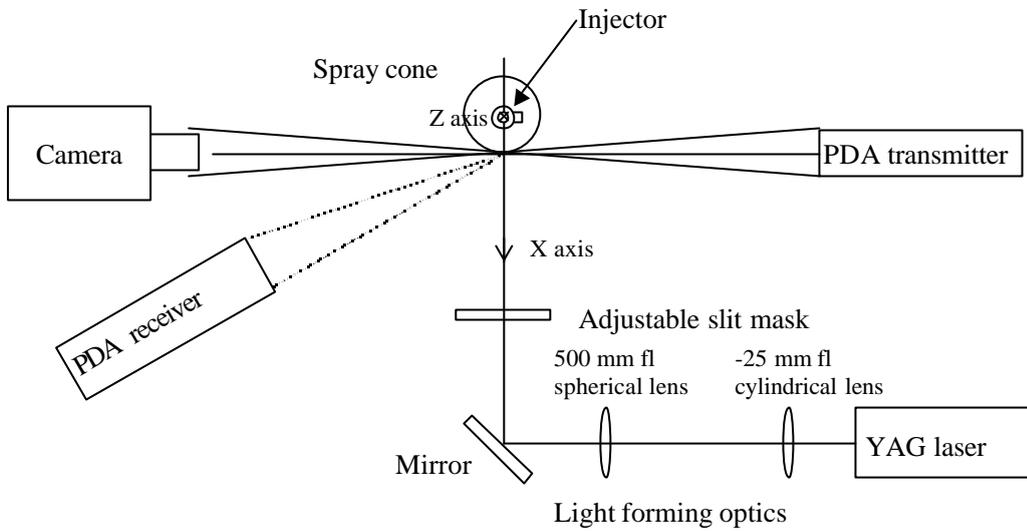


Figure 3: Experimental set-up from above

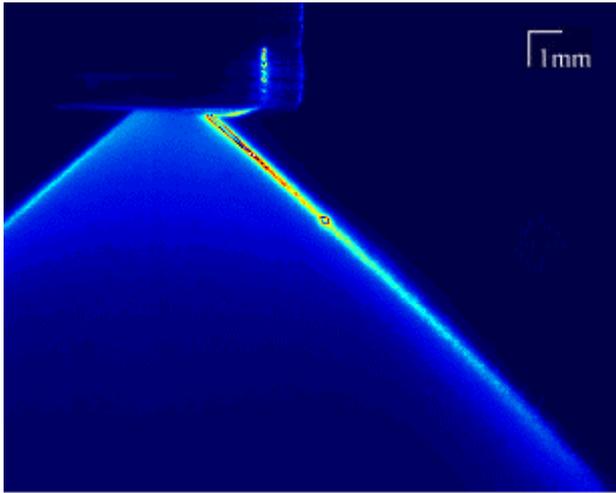
Results

The experimentation is performed with a different injector, which provides a swirling hollow-cone spray for spray guided DI combustion. The injector is operated at a pulse duration of 2.5 ms at atmospheric ambient conditions. The test fluid is indolene, pressurized at 200 bar.

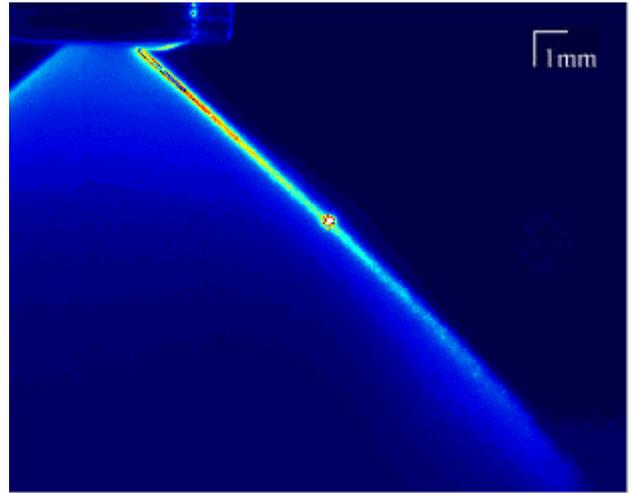
Measurements are done from 13 mm below the injector tip down to 10 mm, 7.5 mm, 5 mm and finally 3 mm distance to the tip. For each vertical distance, the radial position of the measurement volume is set inside the liquid spray sheet coming out of the injector (for convenience this region will be called liquid sheet although it is a combination of liquid elements, ligaments and droplets, forming the densest part of the spray cone). The precise position of the probe volume is set by using the camera, and looking at the synchronized image at a delay time of 1.5 ms after the injection pulse. After visualizing the complete development of the spray, this timing is chosen as being the most representative one.

The images of figure 4 show the exact position of the probe volume for the five vertical positions. The intersection of the four PDA laser beams with the liquid sheet appears on the image as one blob. When the probe volume is out of the liquid sheet, it appears as two crosses, one where the four beams enter the liquid sheet, and one where they exit. These crosses are overlapping on the image, because the PDA transmitter and the camera are set with the same optical axis. By doing so, the PDA probe volume location is known with accuracy and during the entire spray event.

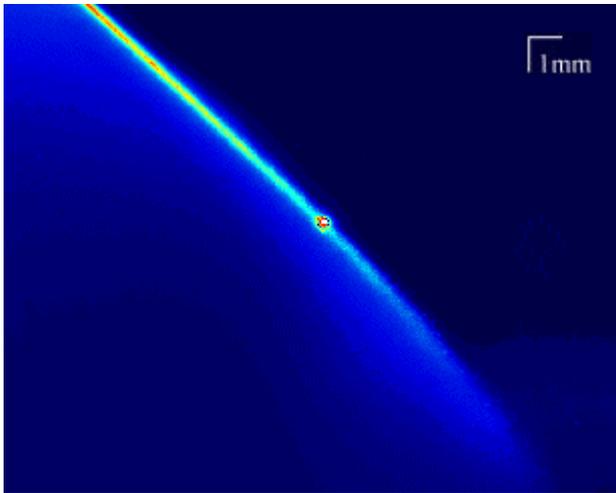
Figure 5 shows the PDA results at $Z = 13$ mm, 10 mm and 7.5 mm taken with the optical configuration #C6 (see table 1). The graphs are scatter plots representing velocities versus delay time. The axial velocity is obtained from pure 1D-LDV measurements regardless of the sphericity of the particle and other criteria specific to the phase measurement. A positive axial velocity is oriented from top to bottom. The radial velocity is obtained from 2D-LDV measurements. A positive radial velocity is oriented towards the center of the spray. The size plot comes from 1D-PDA measurement.



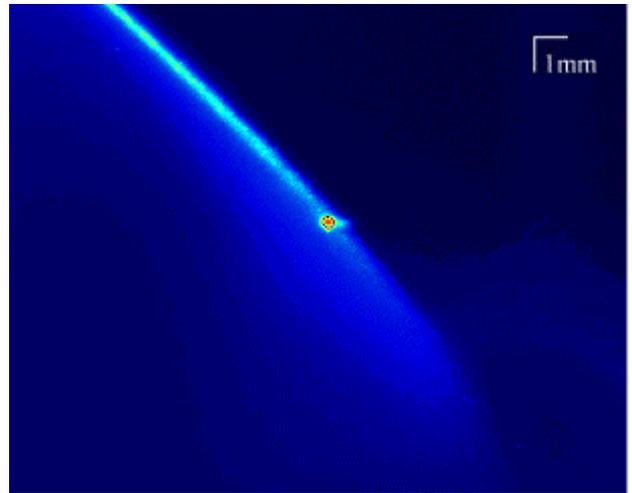
Z=3 mm, X=4.5 mm



Z=5 mm, X=6.7 mm



Z=7.5 mm, X=9.3 mm



Z=10 mm, X=12.1 mm



Z=13 mm, X=13.9 mm

Figure 4: Synchronized images obtained by laser sheet illumination with simultaneous visualization of the PDA probe volume at 1.5 ms delay time.

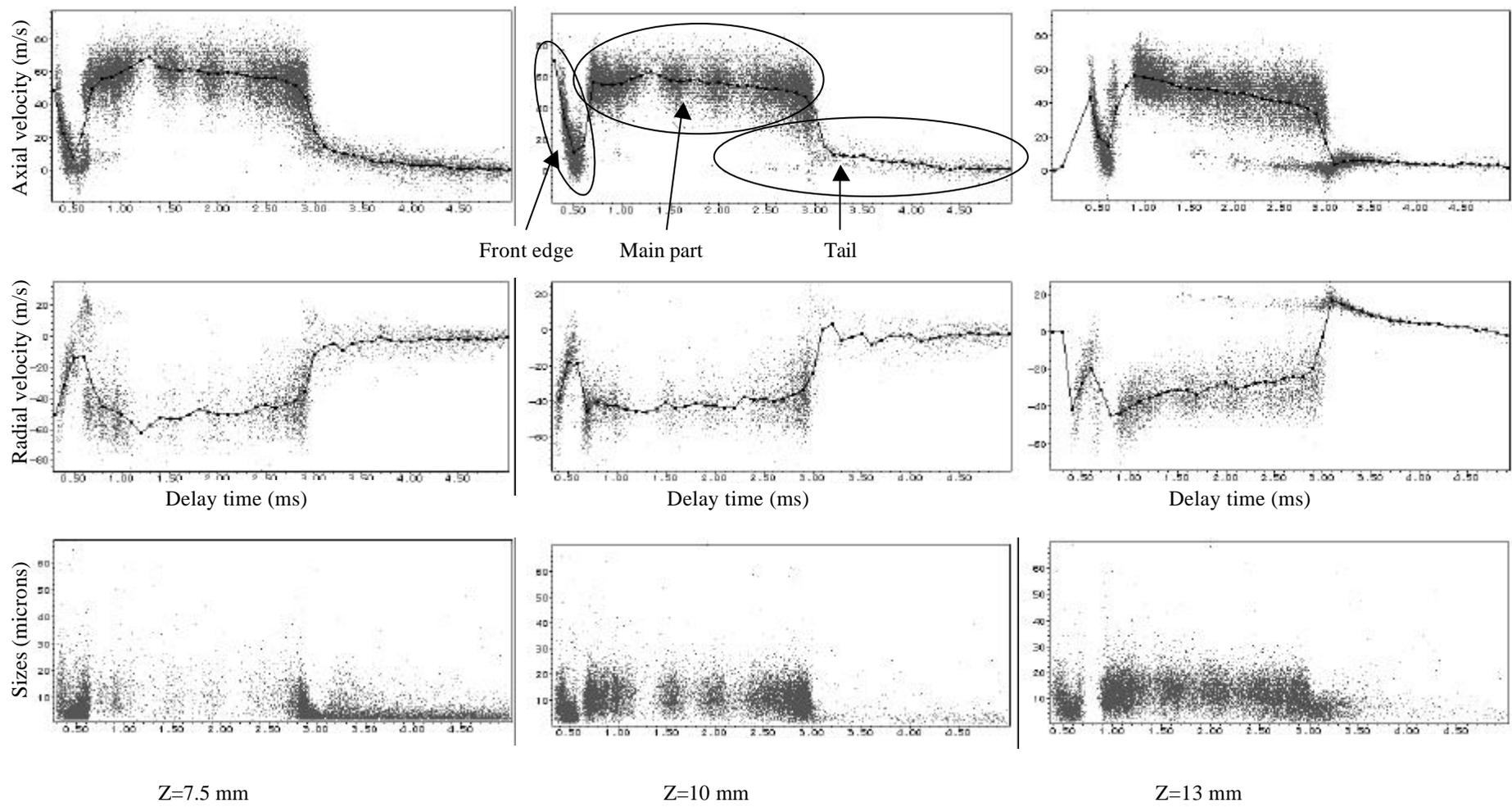


Figure 5: Velocities and size vs. delay time measured at 7.5 mm, 10 mm and 13 mm down from the injector, with optical configuration #C6.

From the scatter plot of velocity vs. delay time, the spray can be easily separated into three phases: the front edge, the main and the tail. With the help of the images, it becomes easier to interpret the scatter plot and especially to determine, whether the main part comes from the edge of the liquid sheet or not, and where the recirculation zone (characterized by negative axial velocity) originates from. For this particular injector, the size measurement of the front edge of the spray does not show higher values than the main spray, in contrast to what is usually observed with inwardly opening injectors.

In the main part of the spray, the scatter plot shows denser and less dense areas, which could be interpreted as an inhomogeneity in the liquid sheet. By carefully selecting the images at particular timings corresponding to high density and low density delay times, the origin of this effect becomes clear. Figure 6 shows a series of zoomed images at $Z=10$ mm, taken at these specific delay times, and showing the evolution of the spray as well as the PDA probe volume location. It is very noticeable that the liquid sheet is in fact slightly wavering up and down creating this inhomogeneity in the scatter plot of figure 5. The high data rate parts (delay times of 1, 1.5, 2, 2.5 ms) come from a probe volume located in the liquid sheet, while the low data rate (delay times of 1.25, 1.75, 2.25 ms) occurs when the probe volume is on the inner edge of the liquid sheet. The dense spray probably acts as a shield and degrades the quality of the Doppler signals sent to the PDA processor due to multiple scattering. This leads to a higher rejection rate of the processor, therefore the number of measured samples decreases.

The liquid sheet thickness measured from the images is $180\ \mu\text{m}$, while the wavering is $150\ \mu\text{m}$ in the horizontal direction at $Z=10$ mm. The corresponding half cone spray angle fluctuates between 46.7 and 47.1 degrees. Although this wavering has a very small amplitude, it is sufficient to significantly affect the data rate of the PDA. This fluctuation of the spray cone angle happens simultaneously for the entire liquid sheet, which explains why the fluctuations observed on the PDA results occur at nearly the same timing, regardless of the vertical location.

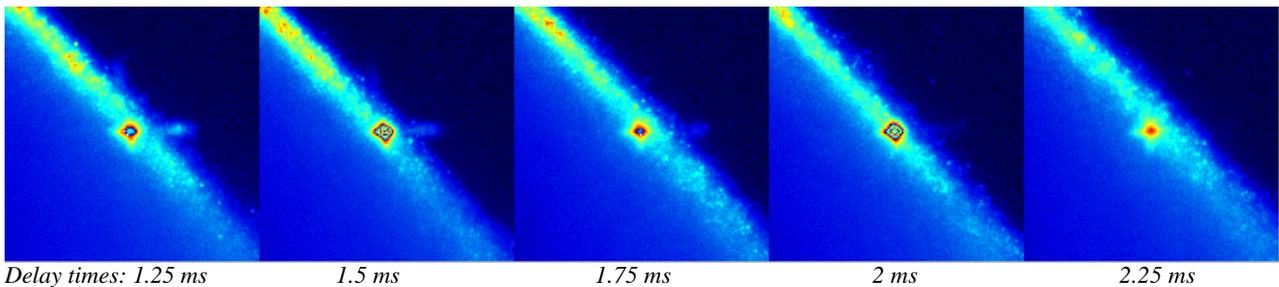
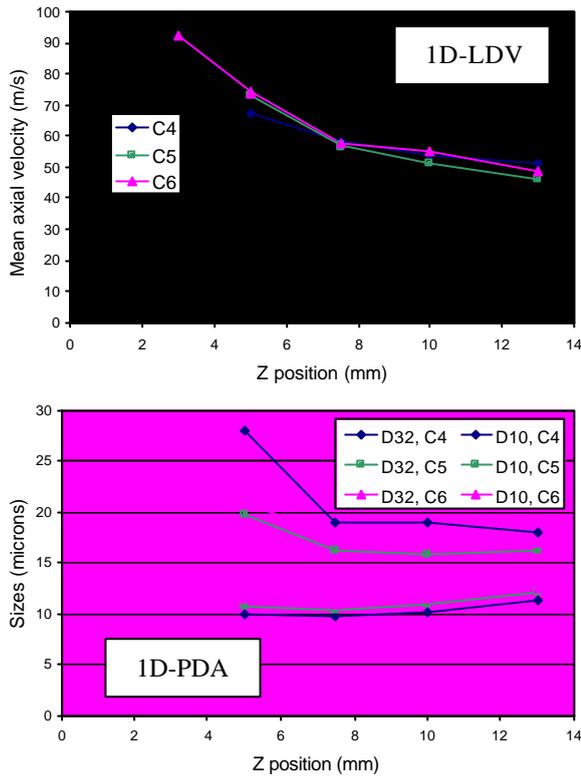


Figure 6: Laser sheet images at $Z=10$ mm, showing the spray wavering and the effect on the PDA probe volume. Image size is $4.4\ \text{mm} \times 4.4\ \text{mm}$.

Thanks to the very precise positioning of the PDA probe volume by using the imaging system, it is possible to change the beam waist (different optical configurations) and to come back to the same point in space with respect to the liquid sheet location. Changing the optical configuration does not affect the results coming from the front and from the tail of the spray, but some differences appear when getting into the main part of the spray, which corresponds to the densest region. This main part of the spray is isolated in the analysis, according to delay time and velocity, using the sub-ranging capabilities of the PDA software. Averaged values are computed and reported in the figure 7.

As expected, the valid data rate drops down when moving the measurement volume up towards the injector orifice. This is a combined effect of the high density of the liquid sheet and the inherent limitations of the instrument, which have been described by various authors (see Bachalo, 1993).

The three optical configurations used here show very similar results from $13\ \text{mm}$ up to $7.5\ \text{mm}$ from the injector tip. At $5\ \text{mm}$, however, the valid data rates decrease and for some configurations the number of samples is not sufficient to create a reliable measurement. The configuration #C4 (smaller beam waist) seems to be very limited when getting closer to the injector. While the configuration #C6 (bigger beam waist) shows the best results in terms of data rate. For size measurements, this is rather unexpected since a smaller beam waist is usually preferred in dense spray regions in order to reduce multiple particles occurrences inside the probe volume. One possible explanation is that the configuration #C4 probably suffers from transit time limitation: the beam waist being small, it creates a short Doppler signal which the processor cannot analyze. Moreover this limitation will bias the averaged velocity by reducing the amount of high velocity particles measured in the scatter plot. This is probably the reason why, when the data rate decreases the averaged velocities go down (see figure 7).



		Valid data rate in Hz				
1D-LDV	Z	3	5	7.5	10	13
	C4	too low	6	110	339	278
	C5	too low	87	171	621	331
	C6	8	97	422	361	696
2D-LDV	Z		5	7.5	10	13
	C4	too low	too low	12	69	77
	C5	too low	2	22	132	140
	C6	too low	6	67	87	205
1D-PDA	Z		5	7.5	10	13
	C4	too low	2	50	206	196
	C5	too low	19	102	429	221
	C6	1	26	237	243	505

Figure 7: Mean velocities and droplets sizes for the main spray, versus distance from injector (Z), and for three optical configurations (see table 1).

Figure 8 shows the scatter plot obtained with the optical configuration #C6, at 5 mm and 3 mm from the injector tip. The scatter plot at Z=5 mm comes from the center of the liquid sheet at X=6.7 mm (see image on figure 4). The lower averaged line comes from the data taken at X=6.8 mm, which is only 100 microns further away from the injector axis. This small displacement of the probe volume is large enough to significantly increase the 1D-PDA valid data rate from 26 Hz (at X=6.7 mm as reported in the figure 7) to 70 Hz (at X=6.8 mm), and the 1D-LDV valid data rate from 97 Hz (at X=6.7 mm) to 183 Hz (at X=6.8 mm). But this displacement of 100 microns also induces a drop of the mean axial velocity of the main spray from 74 m/s (at X=6.7 mm) to 66 m/s (at X=6.8 mm). Thanks to the use of the imaging technique to locate the PDA probe volume, it is clear that the data taken at 6.7 mm are more representative of the dense part of the liquid sheet. Using only the data rate to locate the dense part of the spray would have led to the wrong position, and the measurement reported as being taken in the dense part of the spray would have been in fact coming from the edge of the liquid sheet for this particular injector.

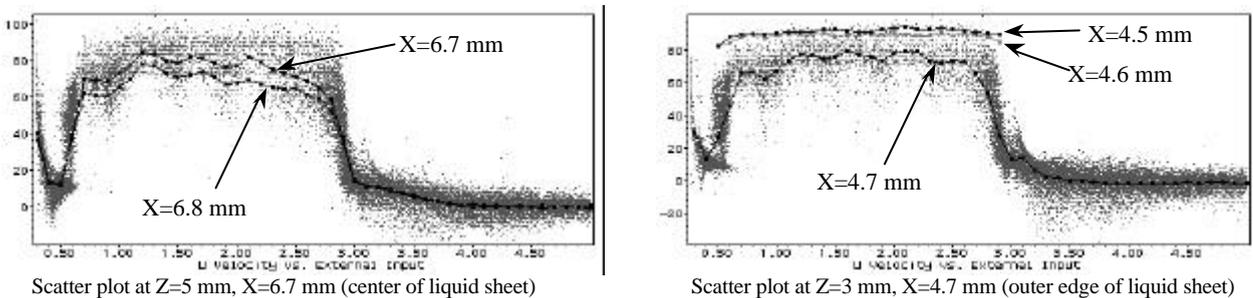


Figure 8: Axial velocity vs. delay time at 5 mm and 3 mm down from the injector, with optical configuration #C6.

Figure 8 (right hand side) shows the result at Z=3 mm but for X=4.7 mm, which is 200 μm away from the position shown in the image figure 4. The two upper averaged lines correspond to radial positions of X=4.5 mm (inside the liquid sheet) and X=4.6 mm. At this vertical location, the current limit of the PDA is reached. The valid data rates for the main spray as reported in the table in figure 7, have dropped tremendously, which makes the measurement very

unreliable. The scatter plot in figure 8 (right hand side) comes from the outer edge of the liquid sheet, which is not representative of the spray contained in the dense liquid sheet. However, the data rate is at 97 Hz for 1D-LDV. By moving the probe volume to the center of the liquid sheet (displacement of 200 μm), the velocities are found to be 20 m/s higher, but the data rates are too small to get reliable data.

Conclusion

A deeper understanding of DI sprays has been achieved by combining drop sizing techniques with imaging. Although the laser diffracting technique provides only spatially integrated data and does not account for the droplet velocities, very helpful information on the part to part and cycle to cycle variations of a single injector can be obtained. For integral time-dependent characterization of DI fuel sprays a combination of the laser diffraction technique with dual view 2D-imaging is recommended. As the results show, a high temporal resolution is crucial to the understanding of the transient nature of DI sprays. Thus, an even higher temporal resolution than the instrument's max. data rate of 2.5 kHz, would be desirable.

For injector design improvements, where it is crucial to achieve a higher spatial resolution and especially to measure closer to the injector exit orifice, the phase Doppler instrument has to be applied instead of the Laser Diffraction technique. When droplet measurement results have to serve as initial condition for Computational Fluid Dynamics, it is necessary to measure as close as possible to the injector tip and in the most representative part of the spray, i.e. the densest region. In order to accurately position the PDA probe volume inside this densest area of the spray, it is proposed here to use the help of a laser sheet imaging technique. For the hollow-cone spray investigated, it has been shown that this method is more reliable than determining the desired position based only on the data rate of the phase Doppler instrument. Due to the inherent limitations of the Phase Doppler, the measurement results can be significantly different between the location of highest droplet density and the point of highest data rate.

For the particular spray investigated here, reliable size measurements could not be achieved for distances closer than 5 mm to the injector tip. In this dense spray region, where typically a larger number of irregularly shaped liquid elements exist, the value of using an instrument that can only detect spherical particles has to be questioned. Probably a combination of PDA with LIF (Laser Induced Fluorescence) techniques could help to overcome these shortcomings.

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