Correlation Velocimeter for Dense Sprays

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Abstract A new optical method for velocity measurement is presented that functions well in optically dense sprays. It is basically a modified Laser-Two-Focus velocimeter with the difference that the data is evaluated by cross-correlation and not by time of flight analysis. This renders the method insensitive to a low signal to noise ratio. The optical set-up is described as well as the errors that can be expected. The measurement foci are separated by a distance of 104 μm and have a measured diameter of 10 μm. The separation of the light beams from each focus is achieved by polarization of the light. The light signal is captured with pin photodiodes and trans-impedance amplifiers with a bandwidth of 28 MHz. The voltages is sampled at 100 MHz with a digital storage oscilloscope and then transferred to a personal computer for evaluation. By using data windows of 10 μs in length the corresponding temporal resolution is achieved. The optical set-up is compact and is mounted on a traverse with 4 degrees of freedom, three for positioning of the foci (10 μm resolution) and a rotation of the foci on the optical axis for their alignment to the main flow direction. With the system measurement of velocities of the spray from a common rail injection system at elevated ambient pressures are presented. Due to the small span wise dimensions of the foci radial profiles of the axial velocity at the nozzle exit were measured.

1. Introduction

The knowledge of the temporal and spatial variations of the spray velocity at or close to the nozzle exit is a necessary requirement for the understanding of atomization, for the development of models and of CFD codes simulating the atomization process. However, standard methods for velocity measurement as Laser Doppler Anemometry can not work well in this region due to the high optical density of the spray. Furthermore, for modern common rail fuel injection systems the spray velocity can reach levels (≈600 m/s) that impose stringent requirements on the bandwidth of the detection system and on the capabilities of the burst analyser. At the same time, the injection duration of these sprays ranges between 0.3 to 2 ms. The duration of the opening and closing transients of the injector are in the order of 0.2 ms. Therefore, a method of measuring the spray velocity is needed that is insensitive to multiple scattering and to a low signal to noise ratio, that needs no assumptions about the tracers that are used and that has the spatial resolution to resolve flow velocity profiles of span wise dimensions of the order of 100 μm as well as a temporal resolution in the order of 10 μs. The method presented here is essentially a modified laser-two-focus (L2F) velocimeter where the evaluation of the signals is performed by cross-correlation and not by time of flight analysis. Basically the same limitations that are valid for L2F, are valid here, i.e. the flow should have a preferential flow direction, so that a tracer that crosses one measuring volume will cross the other volume with a high probability. Therefore, the measuring volumes have to be aligned with the flow. The present optical set-up is a further development of an imaging correlation velocimeter that was used for atmospheric injection experiments, Chaves et al. (1993, 1998). The basic idea in this case is the same, i.e. the correlation of signals from two measuring volumes. However, the measuring
volumes were defined by placing light fibres in a strongly (>50x) magnified image of the area of interest. This set-up gives satisfactory result for atmospheric conditions, see also Schugger et al. (2000), but it cannot be applied to experiments performed in a pressure chamber because the minimal distance between the magnifying lens and the spray is determined by the thickness of the windows of the chamber. The resulting distance between the lens and the image plane would be in the order of a few meters. Such a set-up would also be sensitive to vibrations and misalignments.

2. Optical set-up

The optical set-up of the method is shown in Figure 1. Light from a laser diode (LD) is split into two beam bundles (limits of the bundles are depicted by green and red lines on the figure) by the Wollaston prism (WP1). The two bundles are characterized by their plane of polarisation. For the optics behind the Wollaston prism it appears as if two point sources are present. They are imaged onto the measurement plane by the lenses L1 and L2 with a magnification of about 1. The resulting two foci have then a size comparable to the source, (measured spot size ∼10 µm) and are separated by a distance that depends on the focal length of the combination of L1 and L2, on the splitting angle of the Wollaston prism and on its position relative to the laser. In our case the separation was set at 104 µm. It is measured with a calibrated microscope objective that images the two points on a screen. Light coming from the foci is collected by lens L3 and split according to its plane of polarisation by a second Wollaston prism (WP2) with a large splitting angle. Lens L4 focuses the light on the ends of two light fibres. At the other end of the fibres the light is converted into a voltage by two photodiodes and corresponding trans-impedance amplifiers. The complete optical set-up is compact, see Fig.2. It is mounted on a 3-d traverse that allows positioning of the measuring volumes relative to the nozzle and can be rotated on the optical axis to align the measurement volumes with the flow direction. The nominal resolution of the traverse is 10 µm.

![Fig. 1. Optical set-up of the correlation velocimeter](image)
3. Injection equipment and pressure chamber

The measurements were performed on a common rail injection system equipped with a single axial one-hole nozzle. The high pressure rail pump is connected directly to a speed regulated electric motor. During operation dissipation in the flow circuit raises the temperature of the fuel. A heat exchanger is maintains the fuel temperature at a more or less constant level. A regulation of the rail pressure is achieved by a PID control that modulates the pulse-width of the control valve at the pump. This allows setting the rail pressure at any desired level up to 130 MPa.

The spray was injected into a pressurized chamber; see Fig.2 that allowed varying the gas density by changing the gas pressure up to 6MPa. However, the most stringent requirement on the pressure chamber results from the velocity measurements. The available high aperture optics, which are necessary to achieve a sufficiently large spatial resolution in depth, limit the distance between the measurement point (within the spray region) and the outer surface of the windows to a value of about 60 mm. On the other hand the visible spray area should be as large as possible along the spray axis. This results in a narrow elongated shape of the chamber. On the top there is a provision for mounting axial single hole injectors. The injection pressure upstream close to the needle seat was measured as well as the rail pressure.

4. Basics of the method and data evaluation

When a drop or ligament or any structure that modulates the light moves past the foci and it has a velocity vector that is aligned with the separation plane of the foci the corresponding signals show a temporal shift. With the separation distance of the foci the velocity can then be calculated. Basically this set-up is similar to a Laser Two Focus Velocimeter (L2F). However, the data obtained by the two photodiodes is evaluated by cross-correlation and not by time of flight analysis as in L2F. This allows to measure even when the signal to noise ratio is low as is the case for dense sprays and where not only one structure occurs within the cross-correlation window. As a matter of fact in the case of dense sprays the signals are not signatures of the obscuration of the light by individual
particles but “holes” in the spray that let some light through, see Chaves et al. (2004).

An important question is: what is the resolution of the method in the direction of the optical axis? This resolution depends on the optical aperture of the transmitting optics. Tracers that are in front or behind the beam waist will only contribute to a light modulation in proportion to the area of the light beam bundle they influence. Therefore, large aperture optics will reduce the effective length of the measuring volumes along the optical axis. In the present case the clear aperture of the lenses was 30 mm for a focusing distance of 60 mm. This gives a length of the measuring volume of about 100 µm, which is comparable to the separation of the volumes.

The output voltages of the photo diodes u(PD1), u(PD2) are amplified by wideband transimpedance amplifiers. Various types of detectors have been used up to now, photomultipliers Chaves (1993), avalanche photodiodes, Schugger (2000) and pin photodiodes as in the present case. The only important parameter is the frequency response of the detectors. A simple calculation gives the needed bandwidth for the detector electronics. Assuming that the velocity of a tracer is 600 m/s and the size of a measuring volume is about 10 µm the transition will occur within 1/60 of a µs giving a bandwidth of about 60 MHz. In the present case the bandwidth of the photodiode-amplifier system was 28 MHz. The output voltages are stored on a digital storage oscilloscope (DSO) LeCroy LT264/M at a rate of 100 MSamples/s. Signal histories with a length of 2 ms are recorded, which is sufficient to resolve an injection of an energizing pulse with a width of 1 ms.

The bandwidth requirements of the method are much smaller than those required by a comparable LDA system.

The data is evaluated by correlating windows of 1000 samples from each signal. The typical duration of a signature is in the order of 1-2 µs, so that window lengths shorter than this value are not physically meaningful. Tests were performed with other window lengths of 200 and 500 samples, which would give a higher temporal resolution. However, the peak value of the correlation was lower for windows shorter than 1000 samples and did not significantly increase for windows of 2000 samples.

For each correlation function the maximum is located and validated if the correlation peak exceeds a minimal value. This value is chosen to give physically meaningful data. In the present cases a value of 0.8 was used. The number of validated velocity values was sufficient and at the same time number of erroneous velocity values was minimal. A sub sampling resolution is achieved by fitting the next three neighbours before and after the peak together with the peak with a parabola and then determining the delay to peak of the fit. This value is used to calculate the velocity. It is stored together with the mean value of the time interval of the window. The procedure would then give a temporal resolution of 10 µs for a sampling rate of 100 MHz. However, the window is shifted only by 250 samples to perform the next correlation. In some cases then data is available every 2.5 µs but this is not the true resolution of the system. The reason for this procedure is that the significant signatures can be at the end of the window and information would otherwise be lost.

5. Measurement errors

The relative error in velocity results from the relative errors in the measurement of the distance between the foci s and those resulting from the time delay errors:

\[ \pm \delta_u = \pm \delta_s + \pm \delta_t \]  \hspace{1cm} (1)

The distance of the foci was measured from an enlarged image with a calibration error of \( \pm \delta_{cal} \) = 0.5%. However due to the finite size of the foci D an uncertainty appears when a tracer crosses the foci in a diagonal manner as depicted on Figure 3.
Fig. 3. Uncertainty due to the finite size of the measuring volumes

With \( s' = D^2 + s^2 \) then

\[
\delta_s \approx \delta_{cal} + 1 - \sqrt{1 - \left(\frac{D}{s}\right)^2} \approx \delta_{cal} + 0.5 \left(\frac{D}{s}\right)^2
\]  

(2)

The values for \( D = 10 \ \mu m \) and for the distance of the foci \( s = 100 \ \mu m \) give in total an error \( \pm \delta_s = 1 \% \).

The relative error in the time delay is determined by the acquisition errors of the DSO (<10 ppm, and therefore neglected) and the error in determining the maximum of the correlation function.

In a straightforward evaluation the error would be:

\[
\delta_u = \frac{u}{s} \int dt = \delta_s + \frac{u}{f_B s},
\]

(3)

where \( f \) is the sampling frequency. This results in an error of 8 \% for velocities greater than 600 m/s for a sampling frequency of 100 MHz.

However, if peak fitting is used (as is state of the art for particle image velocimetry) the errors in time delay are greatly reduced e.g. Bendat et al. (1986):

\[
\delta_\tau = \frac{0.3}{B \tau} \left(1 + \frac{SNR^{-2} + 0.5SNR^{-4}}{BT}\right)^{0.25}
\]

(4)

Here \( \tau \) is the delay to the maximum of the correlation function, \( B \) denotes the bandwidth of the system, \( T \) the length of the correlation window and \( SNR \) the signal to noise ratio. This equation is only valid if the sampling theorem is fulfilled, i.e. the highest frequency component of the signal is smaller than half of the sampling frequency. This was achieved in our case by a low pass filter in the DSO with the bandwidth \( BW \) at 30 MHz. For low velocities the bandwidth of the signal is smaller than that of the electronics. It can be estimated by \( B = u/D \). Therefore in total the measurement error is (for \( SNR > 10 \)):

\[
\delta_u \approx \delta_{cal} + 0.5 s \left(\frac{D}{s}\right)^2 + \frac{0.3}{s} B^{-1.25} T^{-0.25} \frac{u}{D} \quad \text{for} \quad B \leq BW
\]

\[
\delta_u \approx \delta_{cal} + 0.5 s \left(\frac{D}{s}\right)^2 + \frac{0.3}{s} B^{-1.25} T^{-0.25} \frac{u}{D} \quad \text{for} \quad B > BW
\]

(5)

Note that the sampling frequency does not appear in this equation anymore. This is due to the sampling theorem that states that if it is fulfilled the signal can be reconstructed completely with a \( \sin(x)/x \) interpolation between the finite sampling points.

Figure 4 shows as an example the errors for the parameters of our measurement system.

6. Results

Exemplarily Figure 5 shows an excerpt of the signals (one window), the signal to noise ratio during the total recording time and the measured velocity for a rail pressure of 80 MPa, a chamber pressure of 0.1 MPa at a distance of one nozzle diameter (200 \( \mu m \)) from the nozzle exit on the spray axis. Data is shown for ten shots, since not for every window position a validated velocity value is obtained. One can see that some velocity values do not fit into the temporal trend of the velocity and that the velocity fluctuates. This is due to the fact that the spray is a turbulent jet. Therefore a criterion was used to discriminate erroneous velocity values. If the value is not within a tolerance band of 20 \% of the temporal mean (i.e. 20\% turbulence intensity) it is discarded.
Furthermore, the velocity history shows opening and closing transients of the injector. There is a time interval during which the velocity remains more or less constant. Mean velocity values were calculated for this time interval for further interpretation.

![Graph showing relative velocity error for different system bandwidth limits.](image)

**Fig. 4.** Relative velocity error for a system bandwidth limit of 30 MHz, a sampling frequency of 100 MHz, a measuring volume size of 10 µm at 100 µm separation and a calibration error of δs of 1%, curve parameter: the length of the correlation window.

One of the advantages of the method is the possibility of measuring close to the nozzle. Figure 6 shows the measured velocity as colour plot vs. the radial position normalized with the nozzle diameter and the time after energizing the injector. This measurement was performed at a distance of one nozzle diameter from the nozzle exit. One can see the radial decay of velocity with larger distances from the spray axis indicating the presence of a rapid core. Also two lobes of lower velocity are present shortly after the opening of the injector at a radial distance of 0.5 diameters. They correspond to small structures (droplets?) that are produced at the surface of the jet and that experience a rapid deceleration. On the upper side this lobe persists during the injection duration. Obviously the spray is not symmetric as was confirmed by shadowgraphy. The velocity reaches a peak on the spray axis at the beginning of injection corresponding to 0.91 of the Bernoulli velocity, which is much higher than what would be expected from discharge measurements.
Fig. 5. Typical signal window, signal to noise ratio and the measured velocity
Figure 7 shows the results of the mean velocity measurements along the spray axis for different chamber pressures (0.1MPa, 1.0MPa, 2.1MPa and 2.7MPa) and injection pressures. The ordinate of this plot is the product of the distance from the nozzle normalized by its diameter and the ratio of gas to liquid density. This allows collapsing the data in a rough manner. The abscissa is the ratio of the mean of the velocity measured during the quasi-steady period of injection to the product of the discharge coefficient times the Bernoulli velocity for each pressure difference.

There is a region close to the nozzle exit where the axial velocity remains high. This corresponds to
a region where primary atomization is starting but the bulk of the liquid is still in form of large structures that are not decelerated by the surrounding gas. At a certain distance (tens of nozzle diameters) that depends on gas density there is a large scatter of the velocity data. This break-up region is characterized by the presence of both large high velocity structures as well as smaller structures with a lower speed. Once primary atomization is completed the velocity decay corresponds to that of a droplet driven spray, i.e. there is still a large velocity difference between the drops and the surrounding gas. The scatter of the data is smaller. Far from the nozzle the velocity decay corresponds to that of a free jet.

There is however some drawbacks when the measurements are performed at room temperature. For rail pressures higher than about 70 MPa the sprays are supersonic relative to the sound velocity of the surrounding gas (pressurized air). The sprays produce weak shock waves (Mach waves) that interfere with the optical method (beam steering). The waves were imaged with backlighting illumination with a 7 ns flash, Figure 8. This was overcome by using relatively large collecting fibre-optics that collects the light even when the beams are deflected by the shocks.

Furthermore there is a region at about 10-20 nozzle diameters, where the signal to noise ratio deteriorates. This leads to a reduction of the validated velocity measurements and to a large scatter of data. In this region the primary break-up of the jet is already effective whilst the volume occupied by the droplets that are being produced is still small. The net result is that the drop number density in this region is maximal. Further downstream the droplet number does not increase as much but the volume the droplets occupy increases and thus decreasing the number density.

7. Conclusions

The method presented here gives satisfactory results in many applications, one of which was presented here. However, the important limitation is that the flow has to have a preferential flow direction in order to apply the method successfully. Turbulent fluctuations do not pose a problem due to the finite size of the measurement volumes. Even for an isotropic turbulence intensity of 10% the lateral displacement of a tracer relative to the mean flow direction would still be within the range of detection of the second measurement volume for the set-up presented here. If the flow direction fluctuates strongly then the method will not give satisfactory results unless one is prepared to evaluate the results as a function of the rotation of the measuring volumes and thus to detect the flow direction as a function of time as well. The same arguments valid for L2F velocimeter apply here too.

One field of improvement of the technique is to apply a dedicated correlation system (hardware?) that would allow a faster evaluation of the signals. At present the evaluation of one data set lasts
some tens of seconds. Also the transfer of the large amounts of raw data between the DSO and the personal computer hinder the evaluation. At present there are no reliable acquisition systems that can be integrated into a personal computer for the required sampling rate.

References


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