Spray Velocity Measurements of a Common Rail Injection System at High Gas Density by Correlation Velocimetry

Clemens Kirmse, Humberto Chaves, Frank Obermeier

Institute of Mechanics and Fluid Dynamics, Freiberg University of Miningand Technology,
Lampadiusstr. 4, 09596 Freiberg, Germany,
Humberto.Chaves@imfd.tu-freiberg.de

ABSTRACT
The knowledge of the temporal and spatial variations of the spray velocity is a necessary requirement for the development of models and CFD codes simulating the atomization processes in engines. For measurements of the spray velocity originating from a fuel nozzle a cross-correlation method is developed. This method allows data acquisition in the optically dense region of the spray near the nozzle exit. The principle of the method, its characteristics and limitations are described. Furthermore, a common rail injection set-up including a pressure chamber is configured for investigations of the Diesel spray injected by an axial single hole nozzle. Exemplarily, the results of velocity measurements along the spray axis for different chamber pressures and injection pressures are presented.

INTRODUCTION

The present report describes the investigation of the unsteady behaviour of Diesel fuel injection by a common rail system of series production and an axial single hole nozzle. Especially, the investigations concentrate on the spray velocity. The measurement method applied previously to steady sprays at low injection pressures has been improved and adapted to this type of system. The spray velocity is measured by a modified Laser-Two-Focus (L2F) correlation velocimeter. Fuel injection is performed into a pressurized chamber at room temperature at densities comparable to those present in a real engine at TDC (Top Dead Center).

1 Experimental set-up

1.1 Set-up of the Common rail equipment and of the pressure chamber

The high pressure common rail pump is connected directly to a 10 kW electric motor regulated by a speed control. Both the motor and the rail pump are mounted on a steel plate vibrationally decoupled from the rest of the set-up. The fuel pump completes the circuit of fuel flow. During operation dissipation in the rail pump raises the temperature of the fuel. Therefore, a heat exchanger is implemented into this circuit to maintain the fuel temperature at a more or less constant level. It has been observed that the response of pressure transducer controlling the rail pressure is sensitive to the fuel temperature. At a temperature of about 50° C the system reaches a stable thermal equilibrium. A regulation of the rail pressure is achieved by a PID control, that modulates the pulse-width of the control valve at the pump.

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, 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 [1]. It allows to vary the gas pressure within the chamber up to 6 MPa. On the top there is a provision for mounting axial single hole injectors.

1.2 Optical set-up of the L2F-system

The laser beam from a laser diode *LD* (50 mW cw output power, 685 nm wavelength) crosses the Wollaston prism *WP 1*, Figure 1, and is split into two linearly polarized beams. They are focused by the lenses *L 1* and

L 2 to two points in the spray region. These foci have a diameter of 10 μm and a separation of 104 μm. Lens *L 3* collects the transmitted and scattered light from the two points. The Wollaston prism *WP 2* separates the beams and the lense *L 4* collects the light after a reflection by prisms onto light fibres, which transmit the light to photo diodes *PD 1, PD 2*. The diameter of the measurement volumes is determined by the size of the emitting region of the laser diode and by the focusing lenses. The separation of the measurement volumes can be adjusted be changing the relative position of Wollaston prism *WP 1* to the lenses *L 1* and *L 2*.

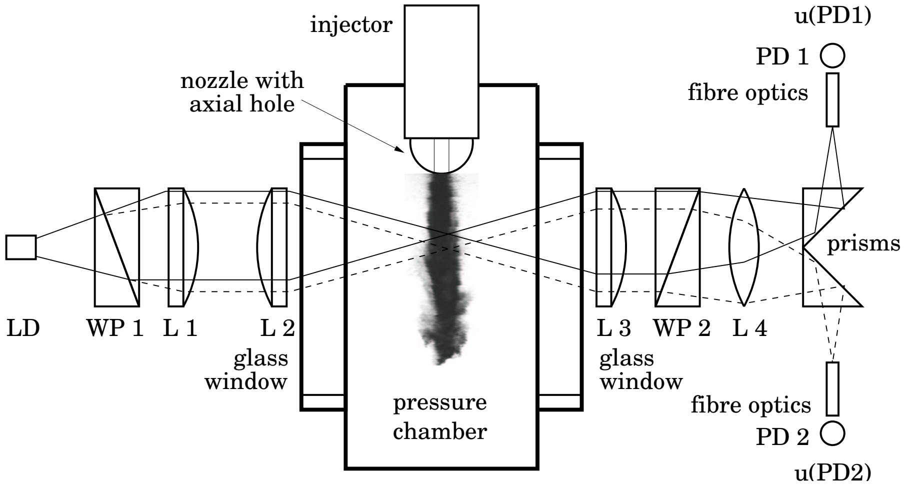

Figure 1: *Optical set-up of the correlation velocimeter*

1.3 4-dimensional traversing system

To reduce the positioning effort for measuring velocity profiles an automated traversing system is used. The optics of the velocimeter is mounted on a XY-table and a linear table which is directed in Z. These tables are controlled by step motors. The traversing resolution is 10 μm. Furthermore, a step motor controls the angle between the measurement direction of the velocimeter (connecting line between the measurement volumes) and the main direction of the spray. Especially for measurements in regions with an radial distance to the axis larger than the nozzle radius this coupling of the directions is necessary to obtain correlating signals.

1.4 Electronic signal processing

The output voltages of the photo diodes *u(PD1), u(PD2)* are amplified by wideband transimpedance amplifiers. Their output voltages are stored by a digital storage oscilloscope (DSO) *LeCroy LT264/M*. With an acquisition 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.

2 Evaluation of the measured data

2.1 Evaluation by cross-correlation with data windowing

After the data have been transfered to a personal computer they are evaluated by means of a cross-correlation method with data windowing of the two stored voltage traces, [2]. The data sets are split into smaller data windows and the correlation is performed for corresponding pairs of windows. These windows do not necessarily have to be disjunct. The reason for using non-disjunct pairs of windows is that it can happen that a significant signature occurs just before the end of the first window and at the beginning of the next window. For non-disjunct windows one signature can then produce a correlation peak in two or more consecutive windows, but because all the data are treated in the same manner no bias is expected. Only when the length of the signature becomes comparable to the window length one would expect a bias towards signatures of shorter length. This corresponds to a high-pass behaviour with a cut-off at about 1 mm in size of the structures.

The velocity resulting from the correlation is allocated to the time corresponding to the mid point of the windows since the velocity is the result of an averaging process. To minimize computation time an expected range of minimum and maximum time delay for the cross-correlation procedure is used. This range corresponds to the expected maximum and minimum velocity. A minimal predefined value (typically 0.7) of the correlation coefficient at the peak is used to validate data. For lower correlation coefficients results are discarded.

To increase the resolution of the resulting velocity an interpolation is performed between the discrete values of the cross-correlation function, [2], [3], [4]. The mean accuracy of the velocity measurement is approximately 3 %.

2.2 Limitations of the optical method applied to very dense sprays

The measurement of spray velocity by means of a cross-correlation method functions well with some limitations in the region of very dense sprays at high gas densities.

2.2.1 Decay of the signal-to-noise ratio with increasing gas density caused by multiple scattering and depolarization effects

With increasing gas density enhanced atomization increases the number of scattering sites along the optical path. If the axial distance between the nozzle exit and the measuring point is in the range of about 20 to 40 nozzle diameters the spray has not widened too much yet and atomization is already effective. This yields a very high number density of scattering sites. For smaller distances atomization has not produced as many droplets yet, and for longer distances the droplets are distributed within a larger volume. Therefore, there is a maximum of droplet number density in a region of about 20 to 40 nozzle diameters. This effect of "multiple scattering" lowers the transmitted light intensity to a signal level comparable to the noise level of the opto-electronic system.

Furthermore, there is an effect of depolarization of the multiply scattered light waves, [5]. Since the separation of the two signals is achieved optically by splitting the light beams according to their polarization the result of this depolarization is a decorrelation of the signals. Consequently, the number of validated velocity data points decreases and the data scatter increases.

2.2.2 Insufficient number of velocity data points for a statistical resolution of the turbulent spray

Fuel injection sprays are very unsteady and turbulent. The correlation velocimeter acquires data only from a single shot. Mean profiles are obtained by averaging the velocity results of ten shots for each measuring point and correlation window. Due to the high level of turbulence of the flow this number is too small. However, an increase of the number of shots would require a prohibitive amount of time.

2.2.3 Modulation of the refractive index of the gas within the chamber by shock waves

Although the pressure chamber is designed to simulate the gas densities present in an engine at TDC it does not reproduce real temperatures. As a consequence, the sprays are supersonic with respect to the gas for most of the time provided the injection pressure is high enough. This is not the case in a real engine, because there the velocity of sound is larger, it increases proportional to the square root of temperature. The following schlieren image in Figure 2 shows how the spray produces a series of Mach waves in the surrounding gas.

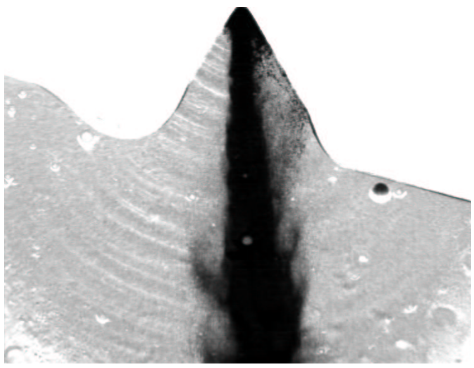

Figure 2: *Shock waves near the nozzle exit (VCO nozzle)*

Unfortunately, these Mach (shock) waves modulate the refractive index of the gas within the chamber and this leads to a deflection of the beams of the correlation velocimeter. The images of the foci are deflected past the core of the fibre optics periodically. This modulation is superimposed on the signals produced by moving structures within the spray. Therefore, a large scatter of the velocity data is detected, since not only the spray contributes signatures to the measured signals but also the shocks.

2.2.4 Effect of the core diameter of the fibre optics

The effect of the core diameter of the fibre optics on the velocity results was investigated by using different core diameters. The intention was to increase the spatial resolution of the velocimeter by decreasing the core diameter. For comparison measurements were performed under the same pressure conditions at a distance of twenty nozzle diameters downstream of the nozzle exit at the jet axis. Figure 3 shows the results of measurements using the smallest and the largest core diameter.

In the case of using the core diameter of $50\,\mu$m the signals have a smaller width than those recorded by using the core diameter of 1.5 mm. The reason for this truncation is the periodical deflection of the images of the foci past the core, (see 2.2.3), caused by the modulation effect of the shock waves. The signal-to-noise-ratio also decreases. Therefore, the resulting "velocity values" increase to a level higher than the expected values obtained from discharge measurements of the nozzle.

Using fibre optics with the larger core diameter results in smoother signals with higher signal-to-noise-ratio. These velocity data fulfill the expectations.

3 Results of the measurements

The injection was performed by an axial single hole nozzle with a diameter $d = 200\,\mu$m and a sharp inlet curvature (*BOSCH DLLA0PV3185842/02*). The energizing time of the injector was kept constant at a value of 1 ms. Ordinary Diesel fuel was injected into the chamber filled with pressurized nitrogen.

Although both radial and axial profiles of the velocity were measured here only the axial profiles are presented due to editorial limitations. The experiments were performed for two injection pressures (80 MPa, 130 MPa) and four chamber pressures (0.1 MPa, 1.0 MPa, 2.1 MPa and 2.7 MPa). The spray velocity is measured along the jet axis in the range from one to 200 nozzle diameters. At each measuring point ten shots are evaluated. The mean values of these velocity data within the quasi-steady region are depicted as points in Figure 4. The lines are fits through the data. The abscissa of this diagram accounts already in a rough manner for the effect of the gas density on the velocity. The scatter of the data does not allow to derive a more precise functional dependence. However, this choice summarizes the data in a sufficient manner.

Furthermore, two straight lines are included into this diagram to indicate the slopes that a self similar free jet behaviour as well as a droplet driven jet behaviour would produce. The intersection points of these lines with the fitted lines are regarded at a measure of the transition from one behaviour to the next.

Close to the nozzle the jets behave nearly like an extruded jet. Of course this is only valid for the velocity along the axis. It may be an indication for the presence of a dense core which is not decelerated by the surrounding gas. However, a closer look shows that there are some differences for the various injection pressures used. Two competing effects can explain this behaviour. On one hand an increase of injection pressure would lengthen this dense core. On the other hand an increased injection pressure enhances atomization by the corresponding increase of relative velocity. It appears that the later effect is more effective at a rail pressure of 130 MPa.

4 Conclusions

A correlation technique developed to determine the spray velocity as a function of space and time yields good results, but with some limitations in the region of very dense sprays in the case of high gas densities. The two foci necessary for the measurement are obtained by optical splitting of a single laser beam into two beams according to their polarization. Since multiple scattering depolarizes the two beams and the intensity of the transmitted light is diminished, the correlation deteriorates. Shocks in the gas phase produced by the jet at room temperature also disturb the measurement.

Normalized axial velocity profiles display three distinct regions in the spray. Near the nozzle the velocity decays in a very moderate manner indicating that the momentum exchange with the gas is not very strong. This is evidence for a dense core. Further away from the nozzle a transition to a behaviour comparable to that of a droplet driven spray occurs. Here still a large velocity difference exists between the droplets and the gas. However, the droplets are decelerated much faster than a dense core. Once the relative velocity becomes small the spray shows the characteristic velocity decay of a free jet.

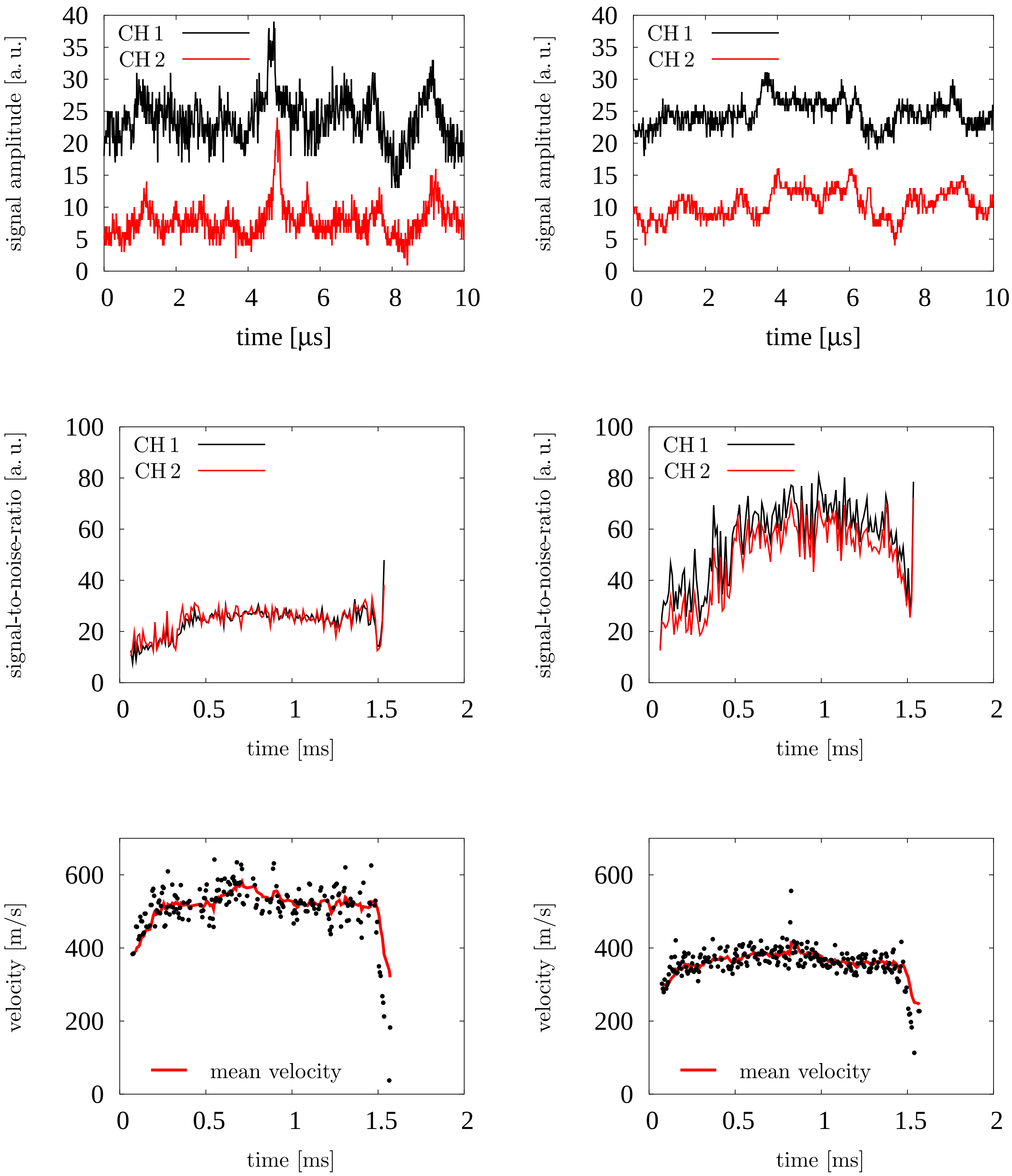

Figure 3: *Typical signal structures (top, zoomed), signal-to-noise-ratio (middle), and evaluated velocity history (bottom) of measurements at the same point within the spray: rail pressure 80 MPa, chamber pressure 0.1 MPa; core diameter of the fibre optics = 50 μm (left hand) and 1.5 mm (right hand), respectively.*

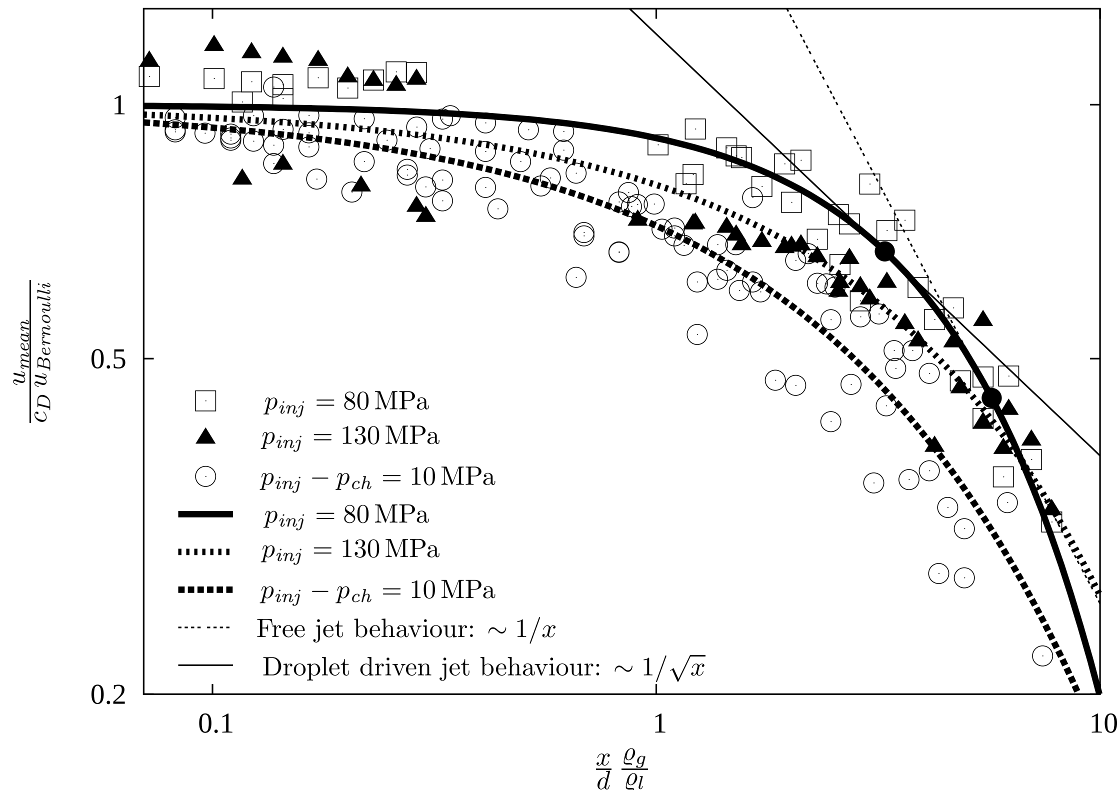

Figure 4: *Normalized spray velocity at the jet axis vs. the product of the distance between nozzle exit and measuring point normalized with the nozzle diameter and the density ratio*

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NOMENCLATURE

d	[m]	diameter of the nozzle	x	[m]	axial co-ordinate
P	[Pa]	pressure	ϱ_g	[kg/m^3]	gas density
u	[m/s]	velocity	ϱ_g	[kg/m^3]	liquid density
Subscripts					
ch	[-]	chamber			
inj	[-]	injection			

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