# Experimental Investigation of the Primary Breakup Zone of High Pressure Diesel Sprays from Multi-Orifice Nozzles

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Nozzle geometry and pressure conditions influence the gas-liquid momentum transfer and the breakup characteristics in the primary break-up zone of high-pressure diesel sprays, and consequently the combustion processes. To investigate these phenomena, different measuring techniques have been used. The spray structure is visualized using High-Speed Cinematography and scattered light imaging. The gas velocities close to the liquid spray are measured using Particle Image Velocimetry to quantify the air entrainment. It is found that the momentum transfer between the liquid phase and the surrounding air strongly depends on the spray structure. Here a sharp edged nozzle inlet promotes cavitation and high turbulence levels in the nozzle hole which leads to stronger break-up and significantly enhanced air entrainment.

## 1 Introduction

New diesel fuel injection systems with injection pressures beyond 100 MPa have clearly improved fuel atomization. Especially Common-Rail systems provide a high degree of flexibility concerning injection pressure and injection timing. These systems allow for multiple injections per cycle, which results in very short injection durations and therefore strong transient effects due to the finite needle lift rate. During the needle opening phase the fuel flow is throttled in the needle seat area, which leads to strong fluctuations in the sac hole and in the spray hole, influencing the primary break-up process of the spray.

The mixing processes in the engine have to be improved to reduce soot formation. One approach is the use of spray holes with strongly rounded inlet edges and conical shape to reduce cavitation and pressure losses, increase the flow velocity and enhance the momentum of the spray. This improves the air entrainment and therefore the mixture formation.

The influence of the spray hole shape on the primary break-up processes for these high speed liquid jets is not yet fully understood. Both, the structure of the cavitation zones and the velocity of the flow in the spray holes have been examined using transparent two-dimensional and three-dimensional nozzles, e.g. [1] and [2]. High-Speed Cinematography and visualizations in backlight and scattered light technique of the primary break-up zone indicate the existence of cavitation bubbles and permit a determination of the near nozzle cone angle [3].

In the work presented here a global characterisation of the primary jet break-up is carried out using a combination of different measuring techniques. Shadowgraphy and scattered light visualization show the spray structure and allow the determination of the near-nozzle spray cone angle. By applying Particle Image Velocimetry (PIV), the velocities of the surrounding air in the near-nozzle area are determined.

## 2 Experimental Setup

In this investigation a commercial Common-Rail system is used. The rail pressure is provided by a pneumatic high pressure pump. Two nozzles with three equally distributed holes and different hole geometries have been investigated. The first nozzle has spray holes with a sharp inlet edge, a constant spray hole diameter of 150 µm and a spraying angle of 162°. The second nozzle has a hydro eroded inlet edge, where the hydroerosion is performed up to a 10.5 % increase in mass flow. This nozzle has a conical spray hole shape with a spray hole inlet diameter of 151 µm, an exit diameter of 137 µm, resulting in a k-factor of 1.4, and a spraying angle of 160°. Both nozzles provide a similar mass flux of about 180 $cm^3/30s$ at 10 MPa rail pressure. See Fig. 1 for a sketch of the injector and the nozzle that shows the orientation of the injector and position definitions for all results presented in this work.

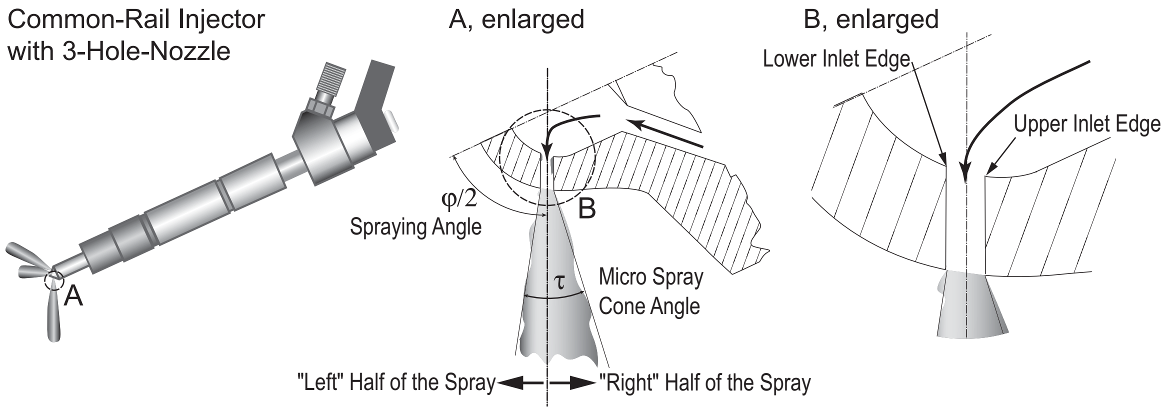


**Fig. 1** Sketch of Common-Rail Injector with an enlarged cutaway view of one spray hole and the definition of the upper and lower spray hole edge

The experimental setup for the High-Speed Cinematography consists of a High Speed Camera (Ultra8, DRS Hadland, 8 images, 500x500 pixels, field of view: 2x2 $mm^2$, max. frequency 100 MHz, intensified, min. gate 10 ns) with a long distance microscope and a photographic flash system (duration approx. 1 ms).

Conventional Particle Image Velocimetry (PIV) has been applied for the measurements of the gas velocities in the surroundings of the near-nozzle fuel spray. The experimental setup is shown in Fig. 2. It consists of a frequency-doubled double-pulse Nd:YAG laser with light sheet optics and a cross-correlation CCD-camera (1280x1024 pixels) with attached long distance microscope. The light sheet thickness amounts to approx. 100 µm. The time difference between both pulses has been varied between 5 and 8 µs depending upon the expected gas velocities. Small water droplets with a mean diameter of 3.5 µm produced by an aerosol generator have been used as tracer particles to visualize the gas flow. A commercial program (DaVis V. 6.0, LaVision, 2001) is used for the analysis of the double frame images with a cross-correlation algorithm. Due to the very small measurement window (2.4x1.9 $mm^2$) and the large flow dynamics an adaptive multi-pass algorithm with an initial size of the interrogation area of 128x128 pixels and a final size of 64x64 pixels has been selected. The relatively large final interrogation window has been chosen to ensure that a sufficient number of tracer particles are evaluated.

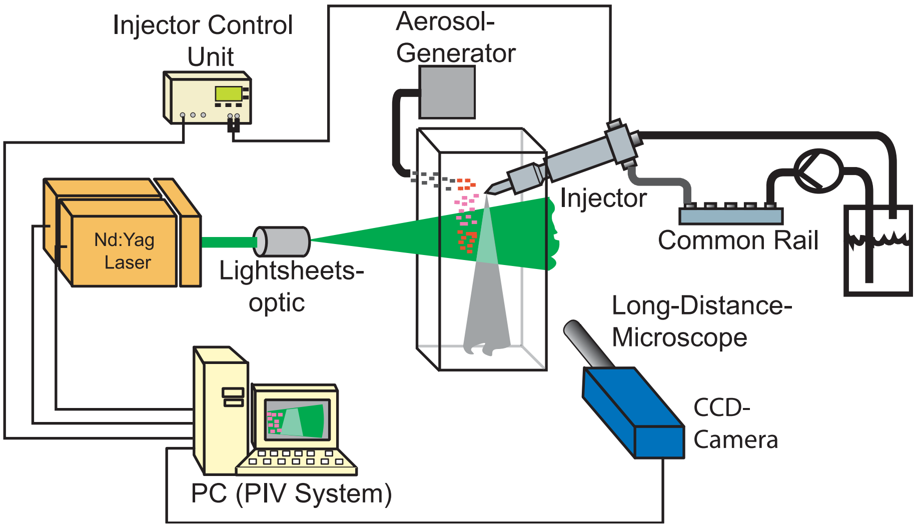


**Fig. 2** Experimental setup for Particle Image Velocimetry in the gas phase.

Due to the high intensity of the scattered light from the liquid first the spray is visualized at very low laser power. For the PIV-measurements the observation area has been shifted towards the outside edge of the spray and the laser power has been increased. Thereby the tracer particles become visible. The PIV-investigations presented here have been conducted at ambient gas pressure in an observation chamber made from acrylic glass.

## 3 Spray Visualizations

### *3.1 Overview*

The influence of rail pressure and nozzle geometry on the spray structure is investigated using High-Speed Cinematography. Fig. 3 gives an overview of the near nozzle spray characteristics for the complete injection cycle for different rail pressures and both nozzle types. The temporal resolution is higher for the start and the end of the injection to resolve transient phenomena. The respective image series are each taken from one injection with an interval of 0.1 ms. Only one image taken 2 ms after energizing the injector represents the quasistationary phase of injection at full needle lift, because the visible changes in the spray characteristics are negligible.
The general spray characteristics are similar for all operating conditions. At the start of injection the needle lift is small and the flow is throttled in the needle seat area with high pressures losses. The inflow conditions to the nozzle hole are fluctuating, leading to strong fluctuations in the spray characteristics with large spray cone angles. For the relatively long energizing time of 2 ms used in our experiments, stable inflow conditions are established about 0.5 ms after start of the injection. Constant spray characteristics are observed during this period. About 2.5 ms after energizing the injector, depending on the rail pressure, the flow in the sac hole becomes unstable again due to the closing needle. When the needle is finally closed, large droplets and ligaments drip from the spray hole.

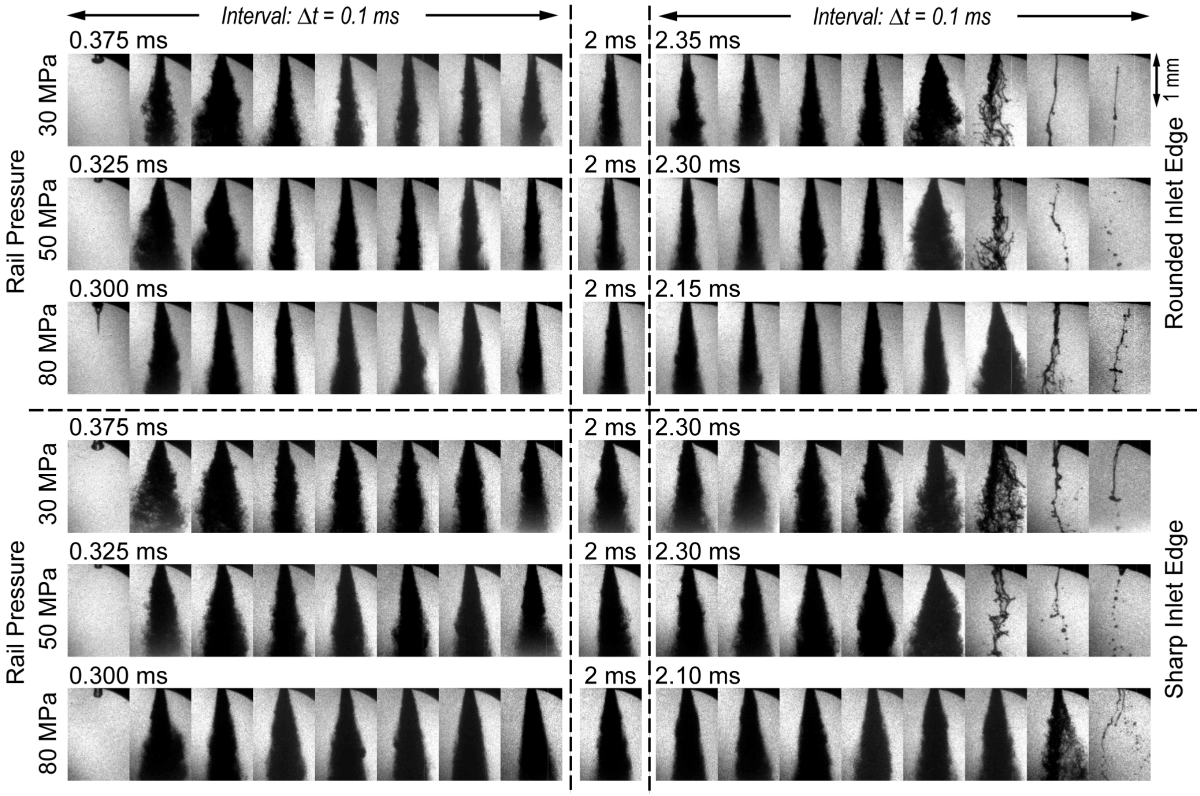


**Fig. 3** Image time series of sprays from both nozzle types; 8 images of the start and the end of injection, each series from a single injection with Δt = 0.1 ms with given time delay after energizing the injector; one image with a delay of 2 ms representing the quasistationary phase

### *3.2 Start of Injection*

The macroscopic fluctuations of the sprays are stronger during the opening phase of the injector. To evaluate this phenomenon, the micro spray cone angle (MSCA) of the investigated sprays has been analyzed. Here, the micro spray cone angle is defined as the full angle between two lines which start at the left or right edge of the spray hole exit and are tangent to the spray boundary 1 mm downstream of the spray hole exit. The results for the starting phase of injection are shown in Fig. 4. Here, the half angles for the left and the right edge of the spray are shown separately. At least 10 images have been evaluated for each point in time.

The MSCA reaches its peak about 0.2 ms after start of injection. This effect is stronger for lower rail pressure and is significantly stronger on the left edge of the spray for both nozzle types. This corresponds to observations presented in [2], where transparent nozzles have been investigated. It is shown that during the opening phase at small needle lift the flow separates at the sac hole entrance, is directed to the bottom of the sac hole and then enters the spray hole at the lower intake edge, corresponding to the left edge in our investigations. A cavitation zone is established at the lower intake edge, leading to higher perturbations on the bottom of the spray hole. After about 0.4 ms this situation changes and the cavitation zone flips to the upper intake edge due to the higher redirection of the intake flow at fully established inflow conditions.

At higher rail pressures the needle lift rises faster and therefore constant nozzle inflow conditions are as well established faster. This explains the wider peaks for lower rail pressures in the time dependent MSCA.

The spray hole geometry plays an important role for the MSCA at fully established flow conditions. The rounded inlet edge in combination with the conical spray hole leads to lower perturbation levels in the primary break-up zone, resulting in reduced near nozzle spray break-up and lower MSCA.

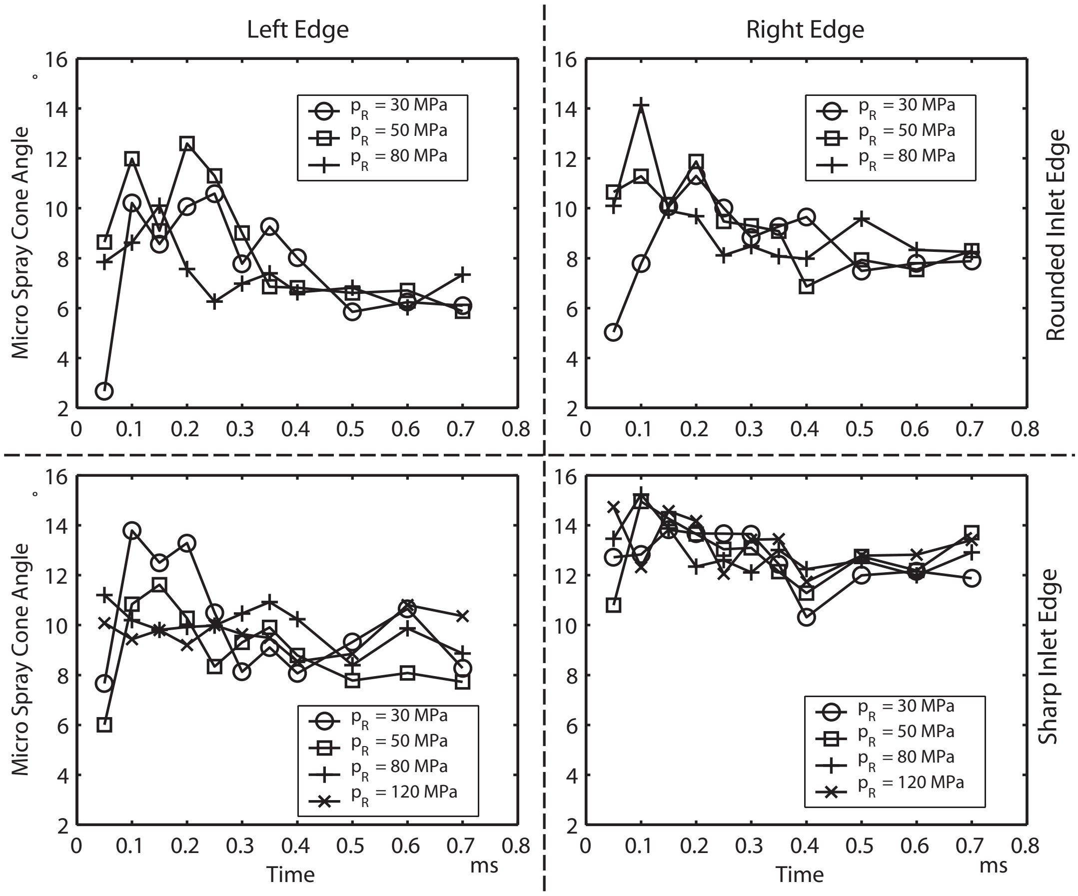


**Fig. 4** Time dependent micro spray cone angle at the starting phase of injection

## *3.3 Quasistationary Phase of Injection*

In Fig. 5 exemplary spray image sequences with a time interval of Δt = 0.001 ms for the left and the right half of the sprays are shown. The images have been taken during the quasistationary phase of injection, 2 ms after energizing the injector.

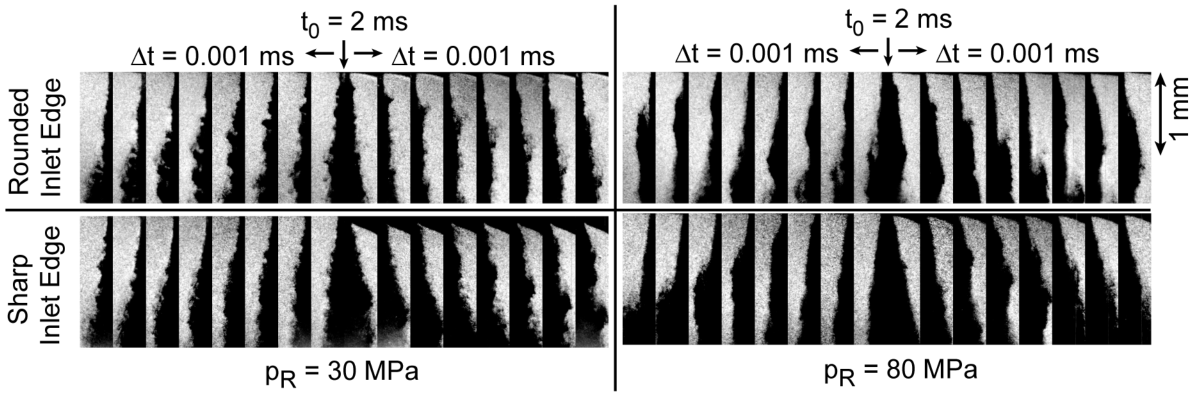


**Fig. 5** Characteristic spray image sequences (divided into left and right part of the spray) for both nozzle types: Δt = 0.001 ms, t = 2 ms, $p_G$ = 0.1 MPa.

The sprays show protrusions on both sides, which move with a significant radial speed away from the spray core. Compared to investigations on single orifice nozzle, the primary atomization is enhanced [4]. For the lower rail pressure of $p_R$=30 MPa smaller protrusions can be identified. A significant influence of the spray hole shape on the primary break-up is not obvious from these single images.
Therefore in Fig. 6 the near-nozzle cone angle is shown as a function of the rail pressure during the quasistationary phase of injection. At least 20 images per operating point have been analysed. Here the MSCA is shown as the sum of the half angles on both sides. For both nozzles the MSCA increases with rail pressure and shows higher values for the sharp edged nozzle. The observed spray direction deviates from the orientation of the nozzle hole towards larger spray angles for both nozzles. A possible reason is the enhanced break-up due to stronger cavitation at the upper (here: right) inlet edge of the nozzle hole due to stronger redirection of the flow.

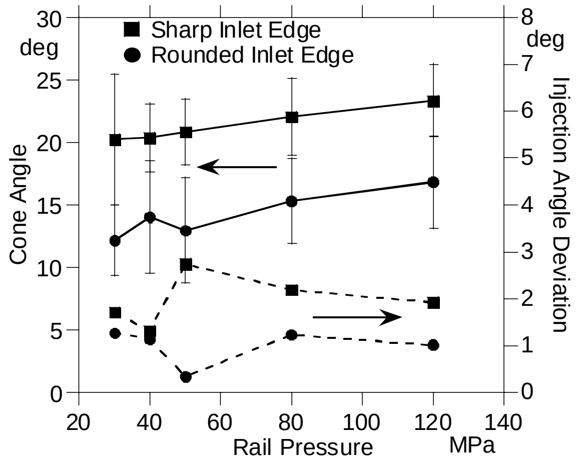


**Fig. 6** Micro spray cone angle and deviation of main injection direction from geometric nozzle hole orientation

## 4 Air Entrainment

Besides the spray cone angle the air entrainment into the spray is an important measure for the momentum transfer between the spray and the surrounding gas.
The gas velocities within the near-nozzle region have been measured using Particle Image Velocimetry at atmospheric gas pressure and rail pressures of 30, 50 and 80 MPa. In Fig. 7 the velocity fields and averaged scattered light visualizations are combined and show the lateral air entrainment into the spray and into its gas boundary layer. The radial component dominates the gas velocities. Close to the spray boundary erroneous vectors can appear due to the weak signal from the tracer particles. The signal is attenuated because of the intensity of the scattered light from the dense spray.

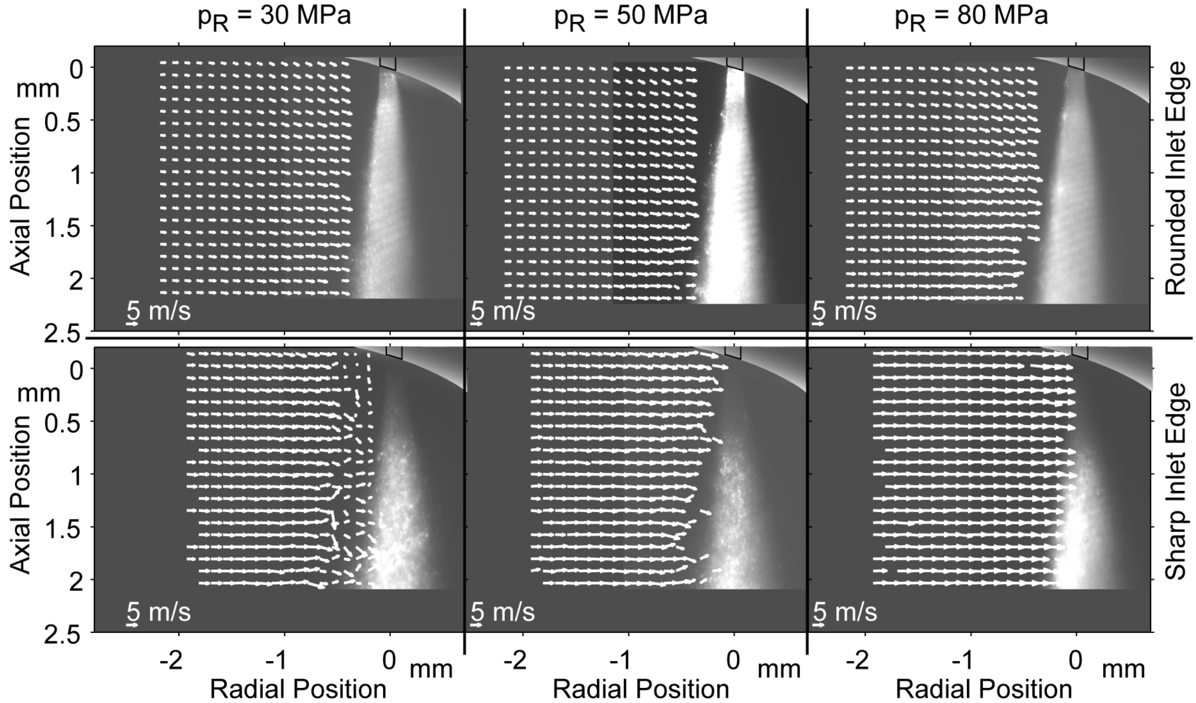


**Fig. 7** Velocity field and scattered light image averaged from 15 images; t = 2 ms, $p_G$ = 0.1 MPa.

Fig. 8 shows the radial distribution of the radial velocity at a plane 1.8 mm downstream of the nozzle exit. The air accelerates towards the spray and the velocities increase with higher rail pressures. The velocity profile does not correspond to the hyperbolic profiles found for one hole nozzles in earlier investigations [4]. The asymmetry of the spray with different break-up behaviour on the left and right side of the spray would require velocity measurements on the right side of the spray. But due to the nozzle tip geometry this area is inaccessible for a laser light sheet.

Because of the enhanced break-up of the spray from the sharp edged nozzle, the amount of entrained air is significantly higher compared to the conical round edged nozzle.

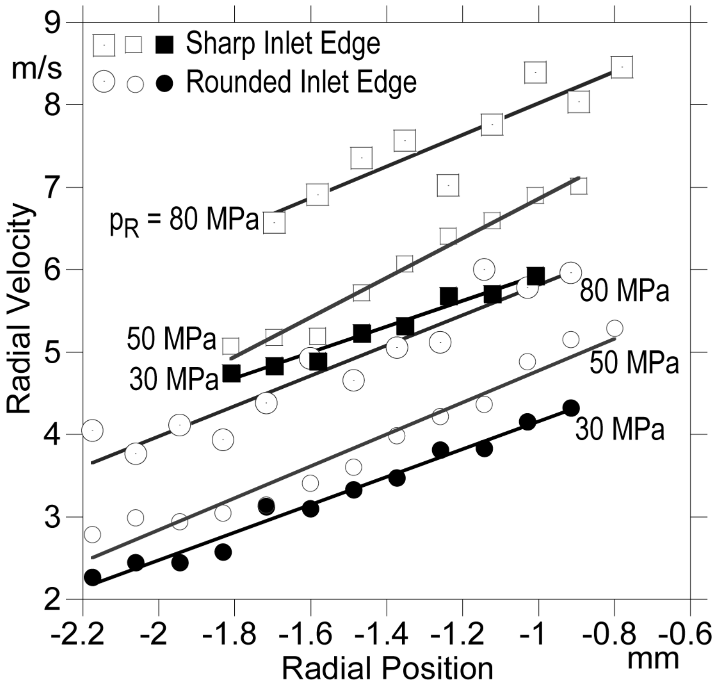


**Fig. 8** Radial velocity distribution 1.8 mm downstream of nozzle exit

## 5 Conclusion

A rounded spray hole inlet geometry in combination with a conically shaped spray hole reduce cavitation and turbulence levels of the internal nozzle flow. Thus the initial disturbances to the spray and the primary break-up decrease, which is evident through smaller micro spray cone angles.

Furthermore the air entrainment is reduced due to weaker primary break-up. Less momentum is transferred to the gas phase in the primary break-up region of the spray and increased momentum transfer and mixing further away from the nozzle can take place.

But transient effects due to the finite needle lift rate at the beginning and at the end of the injection produce very large micro spray cone angles with partly very large structures and strongly enhanced momentum transfer to the gas phase. This problem is not affected and can not be alleviated through modifications of the spray hole shape.

## 6 Acknowledgements

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## 7 References

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