Investigations of Twin-Jet Sprays for DISI Engine Conditions

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Abstract

A well atomized spray enhances the evaporation process in gasoline engines. This work studies a sheet break-up mechanism formed by two impinging jets as a more effective alternative to the commonly used pressure driven break-up in multi-hole nozzles.

A multi-hole injector was modified to produce two impinging liquid jets by mounting different nozzle plates on the modified top of the injector. The sprays produced by the hole-pairs of varying diameter and impinging angle were investigated with different optical measurement techniques: For the investigation of the macroscopic spray structure shadowgraphy and laser lightsheet illumination were used. To quantify the quality of the atomization process the sprays were investigated with Phase Doppler Anemometry. The atomization quality was compared to the spray of a commonly used multi-hole injector particularly with regard to drop size and drop size distribution. The spray of the twin-jet injector showed a finer dispersed spray and less dependency of the mean drop diameter on injection pressure, while good atomization (D_{10}<10µm) was also found for comparably low injection pressures of 5MPa. This value is taken from spray phase with fully opened needle where the twin-jet injector - compared to the multi-hole injector - reduces the mean drop diameter about 21 percent for an injection pressure of 20MPa, and even 38 percent for 5MPa injection pressure.

Introduction

In modern gasoline engines the fuel injection is commonly carried out with multi-hole injectors which are driven by solenoid actuation. An essential task for the injector is the atomization of the fuel to small droplets to improve evaporation and mixture formation. The break-up of the fuel in multi-hole injectors is not very efficient and therefore, atomization is enhanced by cavitation in the nozzle in case of gasoline direct injection where fuel pressures are much lower than in the Diesel case. This cavitation brings down the droplet sizes dramatically but, it also creates a lot of instabilities in the spray process.

This study investigates an alternative break-up mechanism and injector geometry to produce sheet break-up for the application in gasoline engines. The liquid sheet in this case is produced by the collision of two liquid jets (compare Figure 1). The break-up of the liquid sheets is known as an effective atomization process and can create a robust spray. The atomization itself is driven by the interaction of the liquid sheet with the surrounding gas, whereby rapidly growing waves are imposed on the sheet [1]. The theory for the developing waves has been studied by Squire [2] and Hagerty [3] for inviscid liquids and extended by Dombrovski to viscid liquids [1].

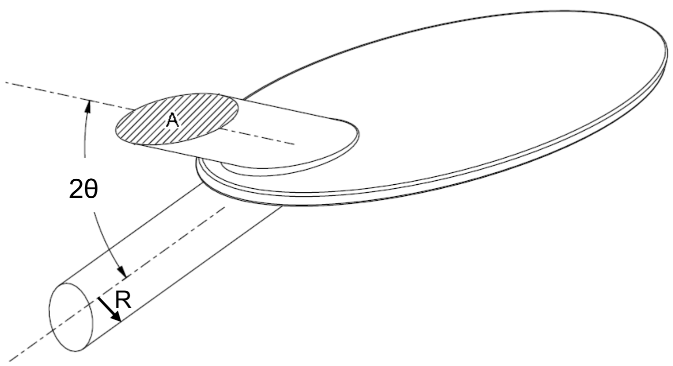

Figure 1 Sketch of two impinging jets forming a liquid sheet

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It is often shown in literature (e.g. Hasson and Peck [4] / Choo and Kang [5]) that the section of the liquid jets parallel to the developing liquid sheet (compare cross section A in Figure 1) indicates the velocity distribution and the shape of the developing sheet respectively, the shape of the developing spray plume.

Hence the macroscopic structure of the spray depends to a large extend on the impinging angle 2θ and the radius of the two liquid jets R. Therefore, one part of this work will focus on a variation of the impinging angle and the bore-hole diameter. A second part of this work deals with a comparison of the twin-jet injector with a commonly used multi-hole injector for gasoline application with regard to penetration depth and atomization quality.

Experimental Setup

For the creation of two intermittent liquid jets a commonly used Bosch HDEV 5.2 multi-hole injector was modified. For this, the top of the injector, where the bore-holes are located, was removed in a grinding process in such way, that the sealing mechanism of the injector is still working. Different plates each equipped with a pair of bore-holes of different geometry (compare Figure 2) were mounted on the grinded multi-hole injector for the creation of the spray.

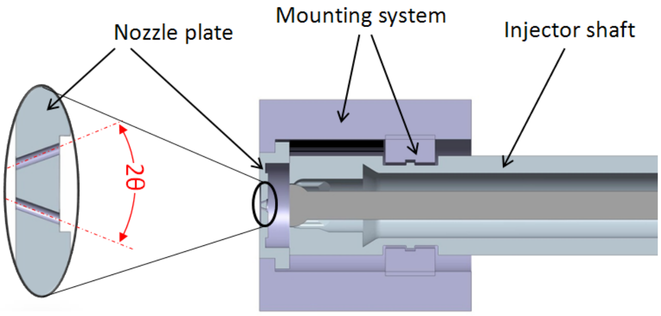


Fig. 2 Sketch of the mounted nozzle plate on the injector

The bore-hole diameter, the impinging angle of the liquid jets and the injection pressure were varied, whereas the ambient conditions were kept constant: pressure of p_{amb}=0.1MPa and a temperature of T_{amb}=350K; the fuel was conditioned to a temperature of T_{fuel}=350K. In a first step these moderate conditions were applied to show geometric parameter influence affecting the twin-jet sprays. Higher ambient conditions causing increased aerodynamic drag and higher evaporation rates will be purpose of further investigations.

For a better overview Table 1 shows the test matrix. The injection time of the injector was set to 1ms.

Tab. 1 Test matrix with varying parameters of the twin-jet nozzle plates

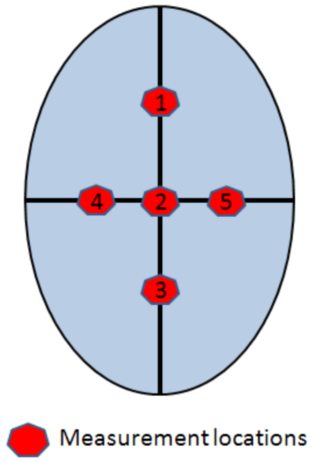
	Bore-hole diameter 2R [µm]	Impinging angle 2θ [°]	Injection pressure p_{fuel} [MPa]
Nozzle I	100	20	20
Nozzle II	100	40	5
Nozzle II	100	40	10
Nozzle II	100	40	20
Nozzle III	80	40	20
Nozzle IV	120	40	20
Nozzle VI	200	40	20

The macroscopic spray structure was studied by shadowgraphy imaging using a flash lamp for illumination and a 12bit CCD camera (PCO sensicam) for signal detection. In a further processing the images are homogenized considering the varying illumination intensity for different regions in the field of observation. An evaluation of the macroscopic spray structure (penetration depth, spray cone angle) was done on base of these homogenized images.

A second focus of investigation was the cross section of the developing spray plume. For this a cross section perpendicular to the spray axis was illuminated by a laser lightsheet formed by cylindrical lenses and a frequency doubled Nd:YAG laser (532 nm) with a pulse duration of about 10ns. In order to assure a homogenized illumination the laser lightsheet was coupled into the pressure chamber from two sides.

To quantify the atomization quality the spray was investigated with Phase Doppler Anemometry in 30mm distance to the nozzle tip in different locations across the spray plume. In the left part of Figure 3 the measurements locations are marked in a sketch of the developing cross section of one spray plume of the twin-jet injector. The measurement positions were located in the inner region of the spray plume for the twin-jet injector as well as for the multi-hole injector. However for the evaluation the results of these measurement positions were merged together.

For the PDA measurements a Dantec PDA system (Dantec HiDense P80), which was supplied by an AR*-laser (max. power 9W multiline, 488 and 514.5nm, Coherent Innova 300), was set up to the optical accessible injection chamber (compare Figure 3 *right*). For this the PDA laser emitter and the PDA detection are mounted on a traverse next to the injection chamber in order to be able to scan the spray at different measurement locations (compare Figure *3 left*). The measurement positions 1,3,4 and 5 were located in the middle between the center of the spray plume (position 2) and the respective spray plume edge. The power of each emitted green laser beams for detection of the diameter was adjusted to 180mW.



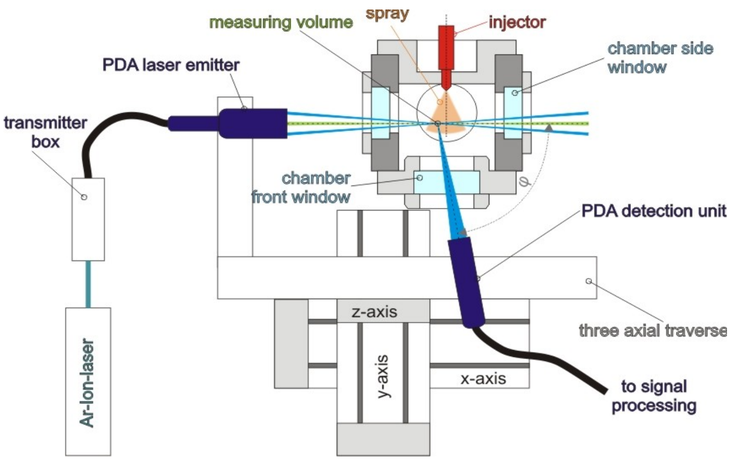


Fig. 3 Measurement locations for Phase Doppler Anemometry in the cross section of the spray plume *(left)* Setup of the Phase Doppler Anemometry measurement system *(right)*

Results and Discussion

Basic spray structure

The impinging angle of the two liquid jets (compare Figure 1) defines the distribution of momentum. A lower impinging angle contributes more to the axial expansion of the liquid, while a higher angle provides more momentum for the impact of the two liquid jets. Therefore, an increasing impinging angle enhances the atomization because of a greater impact of the two jets, but also leads to a broader spray with less penetration velocity.

Comparing the sprays for the two different impinging angles $2\theta=20°$ and $2\theta=40°$ in Figure 4 a higher momentum in axial direction resulting from the smaller impinging angle leads to a higher penetration and to a smaller spray cone angle (cone angle measured in the plane, where the liquid sheet is formed: compare Figure 1). Furthermore, the spray of the smaller impinging angle shows more unstable shape indicated by a conspicuous increase of standard deviation of the spray cone angle and spray direction.

However, for all investigated operating conditions, a turbulent sheet break-up occurs resulting from high Reynolds numbers of more than 60,000 (using Bernoulli's law for calculation).

Li and Ashgriz [6] showed a change from an open-rim sheet atomization to a turbulent atomization (impinging angles $2\theta = 60°...120°$) at Reynolds numbers of about three to four thousand. They also observed a more stable spray with increasing impinging angle while they were studying different sheet break-up mechanisms for different impinging angles and different Reynolds numbers of the liquid jets. A correlation between the laminarity of the liquid jet flow and the developing break-up mechanism was pointed out.

Kampen et al. [7] investigated different "break-up patterns" and showed a change from a "ligament structure break-up" to a "fully developed pattern" for Reynolds numbers around twenty thousand (water~ 18,000; n-heptane ~ 23,000).

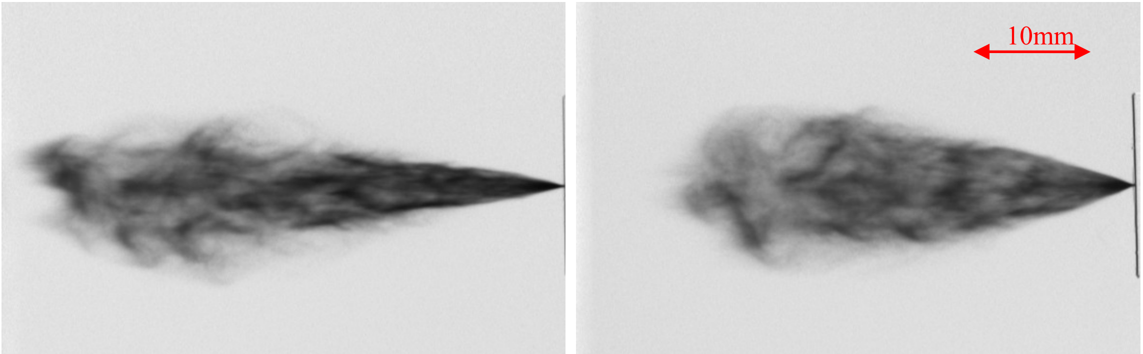


Fig. 4 Homogenized shadowgraphy single shot images of the twin-jet injector spray *(left: 2θ=20° / right: 2θ=40°)* acquired 450µs after visible start of injection
Parameters: p_{fuel}=20MPa, p_{amb}=0.1MPa, T_{fuel}=350K, T_{amb}=350K, injection time: 1ms

The second geometric factor influencing the shape of the spray is the diameter of the two impinging jets. In Figure 5 homogenized single shot images for three different bore-hole diameters – 80µm, 120µm and 200µm – are shown, whereupon the length-to-diameter ratio and the impinging angle (40°) was kept constant. The contour plots of average images calculated from 32 single shot images for the different bore-hole diameters are printed in Figure 5, too. Both, the penetration depth and the spray cone angle in the plane of the liquid sheet (!) are changing with the bore-hole diameter.

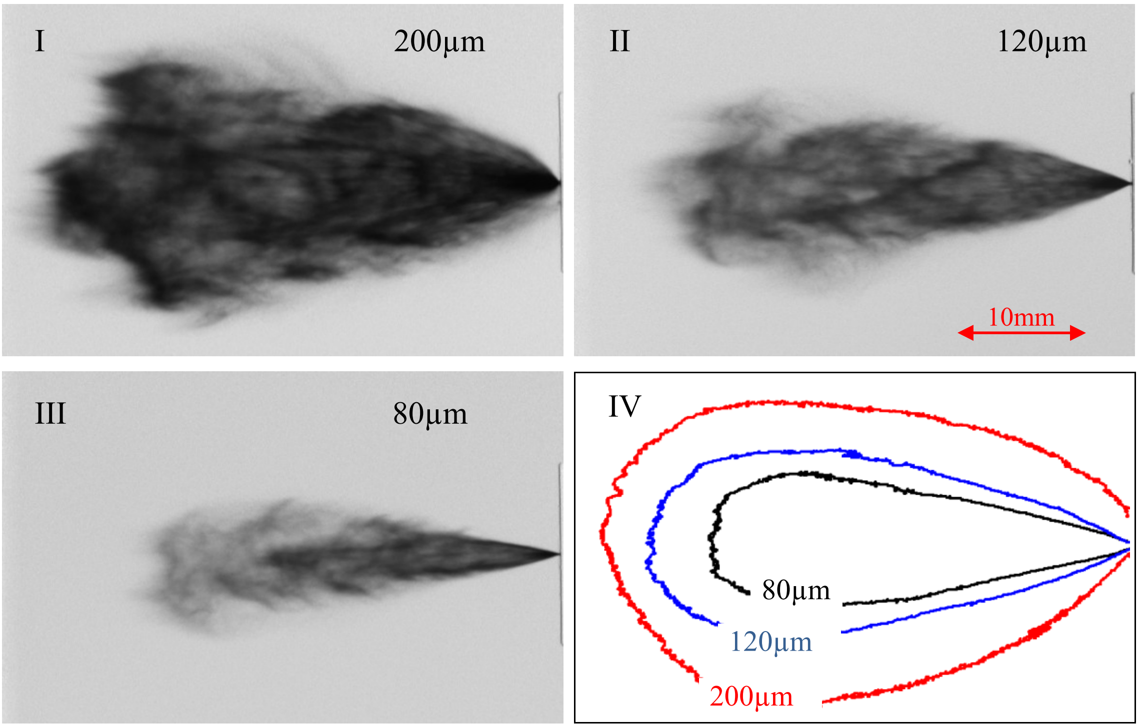


Fig. 5 Homogenized shadowgraphy single shot images for different bore-hole diameters (I-III) acquired 450µs after visible start of injection; Contour plot of average images (IV) calculated out of 32 single shot images for three different bore-hole diameters acquired 450µs after visible start of injection
Parameters: p_{amb}=0.1MPa, p_{fuel}=20MPa, T_{fuel}=350K, T_{amb}=350K, injection time: 1ms

While the spray of the 80µm bore-hole diameter shows a quasi linear increase of the radial spray penetration and a small cone angle in the near nozzle region of the spray cone, the shape and cone angle get broader and more parabolic for an increase of the diameter.

To summarize, the penetration depth and the cone angle can be adjusted in combination with nozzle-hole diameter and impinging angle, which allows the adjustment of both, mass flow and spray shape.

Another possibility for the adjustment of the mass flow is of course an injection pressure variation. The contour plots in Figure 6 show a variation of the injection pressure where different penetration velocities but constant cone angles in the main radial expansion direction can be noticed.

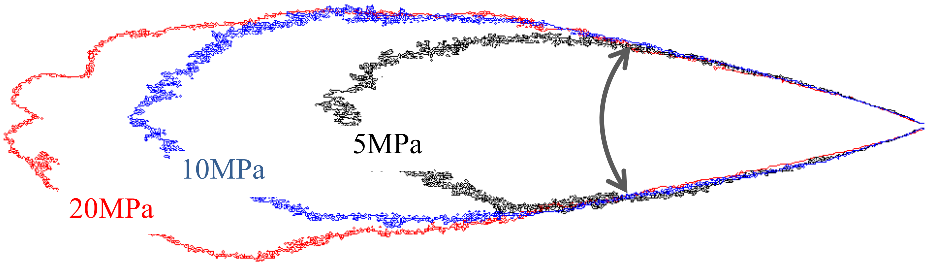


Fig. 6 Contour plots calculated out of 32 single shot images for three different injection pressures acquired 450µs after visible start of injection, bore-hole diameter: 100µm, impinging angle: 40°
Parameters: p_{amb}=0.1MPa, T_{fuel}=350K, T_{amb}=350K, injection time: 1ms

Concluding from both, the variation of the bore-hole diameter and the injection pressure, it can be stated, that the spray shape changing for varied bore-hole diameter is not only produced by a higher mass flow and therefore a higher momentum of the two impinging jets. Size of the impinging area also influence the resulting spray in a way, that – for a constant impinging angle– an increased interaction area creates increased cone angles.
The change of the injection pressure does not influence the spray shape in its main direction (in the plane of the liquid sheet), but – s. Figure 7 – the layer perpendicular to it. In Figure 7 cross sections of spray plumes of the twin-jet injector are plotted for three different injector pressures. The cross section of the developing spray plume shows an elliptic form, whereas the size of the semi-minor axis of the ellipse changes with varying injection pressure. The size of the semi-major axis is found to be constant in the pressure variation – compare Figure 6 –, which results in a broader form of the ellipse with increased injection pressure.

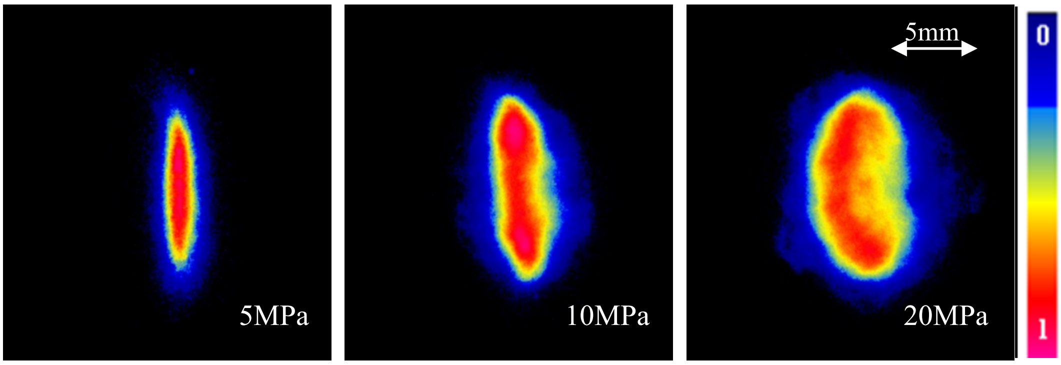


Fig. 7 Average laser lightsheet images calculated out of 32 single shot images for three different injection pressures in a distance of 30mm to the nozzle tip
Parameters: p_{amb}=0.1MPa, T_{fuel}=350K, T_{amb}=350K, injection time: 1ms

An evaluation of the ratio between minor and major axis of the developing ellipses is shown as a function of injection pressure for a fully open injector in Table 2.

Tab. 2 Ratio of the minor and major axis of the developing ellipse

Ratio of minor and major axis	
5 MPa	0.22
10 MPa	0.43
20 MPa	0.52

Comparison to a commonly used multi-hole gasoline DI-injector

In a next step the spray plume of a twin-jet injector (diameter ~ 100µm, impinging angle 40°) is compared to a quasi mass-flow equivalent spray plume of a multi-hole injector (length-to-diameter ratio ~ 1.2, diameter ~ 155µm). The comparison of the penetration depth (compare Figure 8) shows a similar characteristic for the start of the injection, which results in a similar capture of the space in an engine. After about 150µs the curve of penetration depth is flattening for the twin-jet injector. At 600µs after actuation of the injector the penetration depth is deviating about twenty-five percent. Considering the need of a limiting spray penetration in order to avoid wall impingement the twin-jet injector shows a good performance. Providing information of the penetration depth for later time steps was not possible here because of the chosen field of observation of about 40mm.

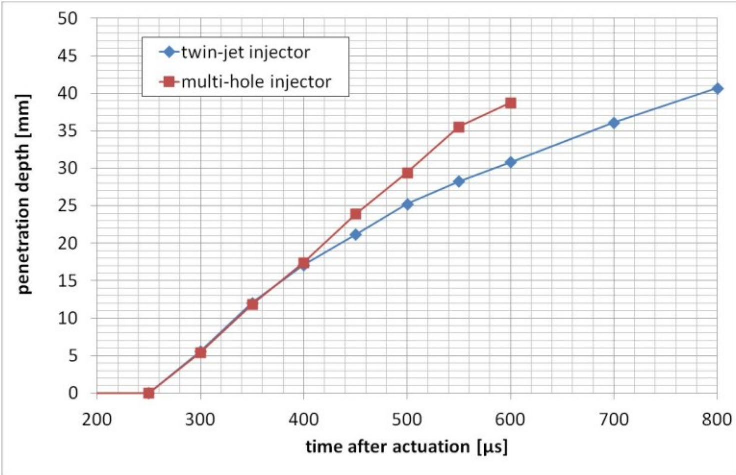


Fig. 8 Penetration of twin-jet and conventional multi-hole injector extracted from contour plots calculated out of 32 single shot images for three different injection pressures acquired 450µs after visible start of injection; Parameters: p_{fuel}=20MPa, p_{amb}=0.1MPa, T_{fuel}=350K, T_{amb}=350K, injection time: 1ms

To the best our knowledge the effect of a smaller penetration depth compared to a multi-hole injector can be observed for all reasonable twin-jet designs and comparable mass flow rates.

To quantify the quality of the atomization process the measured mean drop size is plotted versus time for different injection pressures in Figure 9. The ambient temperature as well as the fuel temperature was set to 350K, the back pressure in the injection chamber to 0.1MPa, again. For all data represented in this paper the actuation time of the injector was set to 1ms.

In the left diagram a typical distribution of the mean drop size versus time of a multi-hole injector can be observed. At the beginning the spray is dominated by big droplets which are produced at the start of the injection when the fluid flow in the nozzle is throttled by the opening injector needle and the sealing seat of the injector. During this opening process the pressure in the sac volume has not reached its maximum.

At the end of the injection – at about 1.5ms to 1.7ms – the drop size increases again because of the throtteling effect of the closing needle. The best dispersion is found in the middle of the process when the needle is fully open.

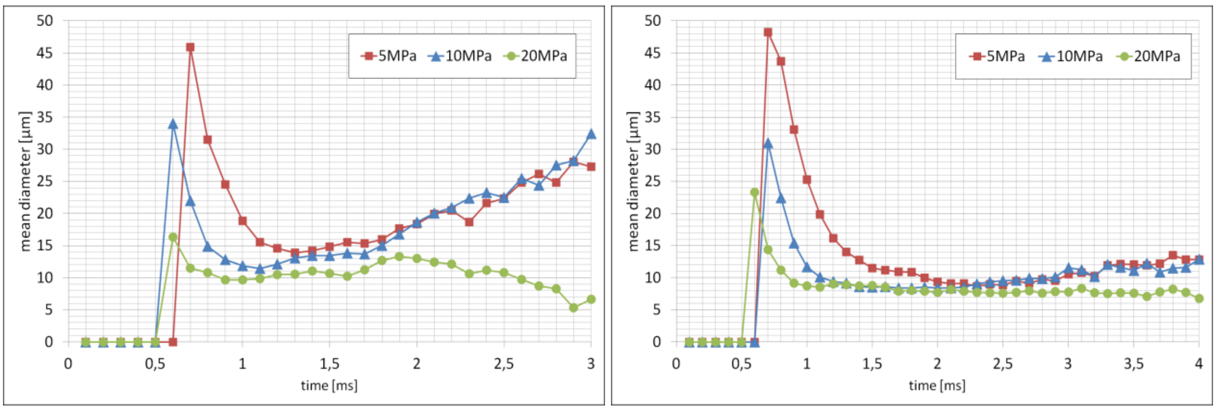


Fig. 9 Measured mean drop size versus time for a Bosch HDEV 5.2 multi-hole injector *(left)* and a twin-jet injector *(right)* for three different injection pressures
Parameters: p_{amb}=0.1MPa, T_{fuel}=350K, T_{amb}=350K, injection time: 1ms;
Data rate: ~ 4000 droplets per calculated average value in a time interval of 0.1ms

Furthermore, the dependency of the injection pressure on the mean drop size for the conventional injector becomes obvious in the left diagram. Changing the injection pressure from 20 MPa to 5 MPa the measured mean drop size goes up about 46 percent (from 9.7µm to 14.2µm) considering the lowest value of measured mean drop size at full needle lift. Also the peak of the mean diameter and the time for achieving a constant minimum diameter goes up rapidly, resulting from a slower filling of the sac hole and a slower penetration velocity at lower injection pressure. For the twin-jet injector (compare Figure 9 *right*) a peak in mean diameter for the spray tip exists, too, and it is even more developed. However, this distinctive peak does not mainly result from the atomization process, but from the prototype assembly of the twin-jet injector. The assembly, where a nozzle plate is mounted in front of the injector, results in a big sac volume between the sealing seat and the nozzle-hole pair, which exaggerates the sac volume of the multi-hole injector by a factor of ten.

In the fully open phase the twin-jet injector shows very a good performance in terms of mean drop size. The dependency of the injection pressure on the mean drop diameter is comparably low. For a pressure decrease from 20MPa to 5MPa the mean drop size increases only ~1.2µm, which is 16 percent. For all injection pressures a quite constant diameter level for a long time span – considering an injection time of 1ms – can be recognized. This effect of the small influence at the injection pressure for present high Reynolds numbers (~30,000 to ~ 60,000 are calculated for the present investigations) has been shown in experimental and theoretical way for this atomization process by Durst et al. [8,9]. They showed that the decrease of droplet size versus increasing Reynolds numbers is very low for Reynolds numbers higher than 30,000, so that nearly a constant average droplet size occur.

It is conspicuous that there is only a marginal increase of the drop sizes due to the throttling at injector closing. A consideration of the drop size as a function of the injection pressure might give an explanation for this observation. In the injection phase at full needle lift the mean drop size shows only a small pressure dependency in the investigated pressure range. As a result the pressure throttling during injection closing has only a marginal influence on the mean dropsize.

Because a fair comparison of the two injector types during injector opening is not possible, because of the prototype assembly of the twin-jet injector with huge sac volume, the focus for comparison is set on the fully open phase of the injection process. In Table 3 the measured mean drop sizes for both injectors are shown for three different injection pressures for a fully opened injector. Here the small pressure dependency of the mean drop size of the twin-jet injector gets clear once more. Considering a pressure change from 20MPa to 5MPa, an increase of 16 percent (1.2µm) for the twin-jet injector is compared to an increase of 46 percent (4.5µm) for the multi-hole injector.

Tab. 3 Mean diameters measured during full needle lift for the two injectors in a distance of 30mm to the nozzle tip

	Bosch HDEV 5.2 min. mean diameter [µm]	Twin-jet Injector min. mean diameter [µm]	Reduction
5 MPa	14.2	8.8	38.0 %
10 MPa	11.8	8.4	28.8 %
20 MPa	9.7	7.6	21.2 %

A comparison of the two injector types at constant pressure levels brings a clear advantage for the twin-jet injector of 21.2 percent for an injection pressure of 20MPa and 38 percent for an injection pressure of 5MPa in droplet size. Furthermore, the level of 8.8µm mean droplet diameter of the twin-jet injector found for an injection pressure of 5MPa is not reached from the multi-hole injector even for a pressure of 20MPa.

In order to underline the small pressure dependency of the mean drop size, histograms for the time ranges, where the spray of full needle lift passes the measurement volume, are plotted for both atomization processes in Figure 10. For the twin-jet injector the curves show a very similar shape. For the multi-hole injector the drop size distribution is obviously changing to smaller drop sizes for increasing injection pressure.

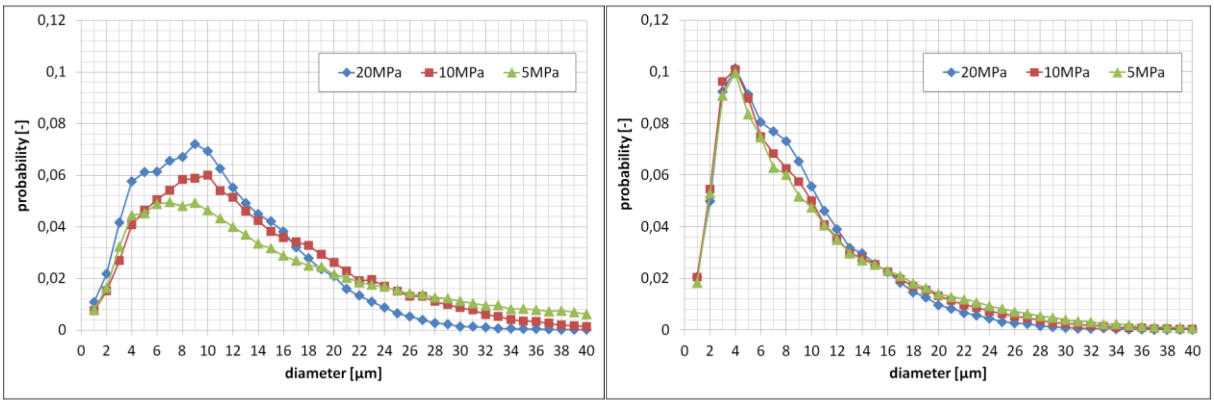


Fig. 10 Histograms for the drop size distribution of the multi-hole injector (*left*) and the twin-jet injector (*right*) for full needle lift and three different injection pressures; Parameters: compare Figure 9

Summary and Conclusions

The focus of this work was to investigate the potential of a sheet break-up mechanism created by two impinging jets for an application in gasoline direct injection. The spray of a prototype injector was investigated with different optical measurement technique and compared to the spray of a conventional multi-hole injector. To study the macroscopic spray structure and the influence of the different geometrical parameters as well as the injection pressure shadowgraphy was used. In was found, that the shape of the spray can be adjusted by the bore-hole diameter and impinging angle. A bigger bore-hole diameter increases both, the spray cone angle and the penetration depth; a bigger impinging angle of the two liquid jets results in an increase of spray cone angle, but decreases the penetration depth.

Comparing the results from shadowgraphy and laser lightsheet measurements an elliptical form of the spray plume cross section was found whose semi-major axis size is not influenced by injection pressure. However, the length of the semi-minor axis shows pressure dependence, in a way that a broader shape is created at increasing injection pressure.

In a comparison to a commonly used multi-hole injector (Bosch HDEV 5.2) the twin-jet injector showed the following characteristics: The penetration depth for the twin-jet injector compared to the multi-hole injector is reduced, which can be positive in order to avoid wall impingement in engines.

At full needle lift the measured mean drop size for the twin-jet injector compared to the multi-hole injector decreases drastically – depending on injection pressure – 21.2...38 %. Additionally, the twin-jet injector shows a much smaller dependency of the mean drop size on injection pressure. This makes atomization characteristic easier to regulate because a lower injection pressure reduces the mass flow but does not impair the atomization quality and hence the evaporation process.

For future work investigations of a nozzle-hole design and the spray stability (shot-to-shot variation / flapping) and of the influence of the back pressure are planned.

However, up to now nothing reliable can be said about the opening and closing behavior of a twin-jet injector resulting from the prototype assembly. For this an injector with reduced sac volume and with an inner nozzle design and inner nozzle flow optimized for this atomization process, is indispensable.

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