Multi-hole gasoline direct injection: In-nozzle flow and primary breakup investigated in transparent nozzles and with X-ray

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Abstract

The contribution describes the flow field inside modern gasoline direct-injection nozzles and sprays. Starting from the internal nozzle flow, results from transparent real-size nozzles are shown, where a significant vapor fraction even for cold fuel conditions is proven. Based on vapor fraction inside the nozzle, evidence for (super-)sonic flow conditions inside the nozzle is shown. The nozzle outlet velocity is determined by means of X-ray structure tracking velocimetry, which is a very powerful measurement technique to gain access to the very dense spray at the nozzle outlet. The X-ray velocities are compared to values that are determined by means of optical—phase Doppler anemometry/laser Doppler anemometry and Schlieren imaging—measurement techniques. By extrapolating the maximum droplet velocities found by laser Doppler anemometry in the more downstream regions of the spray to the nozzle outlet region, very similar velocities to the one derived from the X-ray measurements close to Bernoulli velocity are evaluated for typical gasoline direct-injection engine conditions. A third access to the nozzle outlet velocity is given by the derivation of penetration curves. The combination of vapor fractions and outlet velocities provides a measure for the initial spray momentum.

Keywords

Gasoline direct-injection, spray, velocity measurements, X-ray, laser Doppler anemometry/phase Doppler anemometry, transparent nozzle

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Introduction

Modern gasoline direct-injection (GDI) nozzles achieve droplet size distributions very close to diesel injectors although injection pressures are one order of magnitude lower.¹ The higher effectiveness in primary atomization is due to the different atomization mechanisms that are dominant for GDI injectors. While ambient pressure and temperature as well as the relaxation of the velocity profile have a high impact on the atomization in the high-pressure diesel case, turbulence and cavitation effects become increasingly relevant for GDI sprays^{2,3} due to the shorter length/diameter ratio of the spray holes as well as the lower viscosity of the fuel. Consequently, the flow inside GDI nozzles has to be treated as a turbulent multi-phase flow throughout the entire process from the internal nozzle flow to the conditions found at the nozzle outlet, that is the primary spray region, and in the fully developed spray.

Analysis of flow conditions in GDI sprays

In literature, various approaches to measure spray velocities can be found. Optical measurement techniques generally are limited in terms of optical density and often velocity range. Therefore, the measurements of velocities in GDI sprays are generally challenging. Laser Doppler anemometry/phase Doppler anemometry (LDA/PDA), which is also used in this article, is

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Figure 1. Image of the transparent static real-size nozzle model and the geometrical equivalents in a schematic real nozzle.

one of the most common spray measurement techniques. It is based on the light scattering of droplets that pass through a fringe pattern that is created by the interference of two intersecting laser beams. It provides quantitative results for droplet velocities and diameters without the need of calibration since it is based on the general solution of the Mie-scattering equations. This, however, requires that only one droplet is in the measurement volume at a time since the scattering signal from two or more droplets cannot be separated due to the non-linear nature of their interactions.⁴ If the optical density is sufficiently low, measurements in the near-nozzle region are, however, possible. Goddwin et al.⁵ showed axial droplet velocities of around 80 m/s for a 5 MPa gasoline spray from a swirl injector in the near-nozzle region. For higher injection pressures and multi-hole injectors, Mitroglou⁶ shows mean velocities of around 110 m/s for 8 MPa injection pressure and 150 m/s for 12 MPa injection pressure at 2.5 mm nozzle distance.

A related measurement principle is used in the laser correlation velocimetry (LCV) method. Here, instead of a regular fringe pattern, the scattering at only two points is used. Those points can be created by two focused laser beams in which case the measurement technique is referred to as “laser two foci” (L2F) approach. Alternatively, the illumination of both points is realized with the same laser beam, and the scattered light is focused on separate detectors by the detector optics. In this case, the measurement technique is referred to as “one laser beam two images” (LB2I) approach.⁷ These techniques are quite robust and are therefore mainly used for diesel applications, while results for GDI sprays are not found in literature. Nevertheless, it is still limited by optical density in the direct vicinity of the nozzle. This general limitation that all optical approaches have in common can be overcome by the use of X-ray radiation with high spatial coherence. The respective measurement approach combines X-ray phase contrast imaging with structure tracking velocimetry,⁸ and results from this technique and details about the setup are shown in this work.

Generally, this article focuses on the flow conditions of gasoline injectors which are discussed and compared

to theoretical flow considerations. The focus is the development of the fuel velocity, starting from the internal nozzle flow, downstream to the nozzle outlet and further to the fully developed spray. In addition, velocity- and pressure-driven phenomena such as cavitation, atomization and aerodynamic drag are considered.

Internal nozzle flow

The internal nozzle flow can be investigated using transparent real-size models of the nozzle. The main challenge is the manufacturing of stable, geometrically similar nozzles and providing the optical accessibility that is needed. Different approaches to both can be found in literature. While Aleiferis and colleagues^{9,10} manufactured nozzles from acrylic glass using drilling techniques, also laser drilling in BK7 nozzles was tested in comparison to conventional mechanical drilling.¹¹ With the development of laser-based manufacturing technologies in recent years, especially the selective laser etching from fused silica,¹² new possibilities in precision and shaping have occurred that enable the manufacturing of nearly arbitrary nozzle geometries. In this work, results from a laser-etched transparent nozzle model are shown. Since the technique only works for fused silica, it is not possible to use the nozzle material as a sealing face for the injector needle. Therefore, the glass nozzle forms a model of the stationary internal nozzle flow simulating full needle lift conditions. The needle seat itself is placed outside of the glass body. Therefore, this setup is only suitable for stationary flow investigations. This setup is schematically depicted in Figure 1. To simulate the flow conditions of a gasoline injector, a strongly abstracted model was used.

Region 1 in Figure 1 simulates the gap between needle and sealing face, region 2 simulates the blind hole in the nozzle tip and region 3 is the spray hole itself. All geometries are chosen to provide the maximum in flow similarity between the single-hole transparent nozzle and the real multi-hole conditions. To this end, a three-dimensional structure was created as shown in Figure 2. The Reynolds number in the nozzle is similar to the real nozzle because both diameter and fluid are

Figure 2. Internal geometry of the transparent nozzle: (a) profile relaxation and (b) circular inlet flow.

comparable and all flow regimes that occur in the real nozzle are represented in the model. We tested injection pressures from 0.2 to 15 MPa, correlating to Reynolds numbers from approximately 1900 to 25,000 in the spray hole for cold fuel. To achieve similarity in the nozzle inlet flow, a step was designed that reproduces the profile relaxation from needle seat to blind hole Figure 2(a)). Furthermore, the blind hole model was designed to allow for a circular inlet flow into the spray hole (Figure 2(b)).

The similarity is especially valid for the fully open needle condition where, in contrast to opening and closing processes, the larger dead volume between sealing and nozzle outlet can be neglected. A series of high-speed images in Figure 3 clearly shows cavitation within the transparent nozzle for 10 MPa injection pressure and moderate fuel temperatures (shadowgraph measurement).

Since the shadowgraph experiment represents the second derivative of refractive index accumulated along

a line of sight, regions which appear bright in Figure 3 can be assumed to be completely filled with fluid (due to the similar refractive index 1.46 of liquid fluid and fused silica). Dark regions mark phase changes/boundaries with a high gradient in refractive index. The phase changes in Figure 3 show cavitation regions. It becomes apparent that even for cold fluid conditions and moderate injection pressures, there are large amounts of fuel vapor inside the nozzle. For the depicted time steps between 740 and 760 μs after electrical start of injection (eSOI), string cavitation^{13,14} is visible. The cavitation string is present through the complete nozzle hole and touches what would be the injector needle in a real injector geometry. This hints at a vortex flow inside the hole and around its inlet. The cavitation is symmetrically developed in this case of a one-sided inflow. Under real engine conditions, both pressure and temperature will be similar or higher, depending on the operation conditions. An increase in temperature would increase the vapor pressure and an increase in injection pressure would increase velocity and turbulence, so both will not decrease the amount of vapor under real engine conditions. The high amounts of vapor will affect the internal nozzle flow.

The speed of sound in two-phase flows is described by the following equation with speed of sound a , vapor fraction α and density ρ .¹⁵ The indices l and g mark liquid and gaseous phases

$$\frac{1}{a^2} = \frac{\alpha}{a_g^2} \cdot \left[1 + (1 - \alpha) \cdot \left(\frac{\rho_l}{\rho_g} - 1 \right) \right] + \frac{1 - \alpha}{a_l^2} \cdot \left[1 + \alpha \cdot \left(\frac{\rho_g}{\rho_l} - 1 \right) \right] \quad (1)$$

The significant vapor fractions inside the nozzle hole lead to a significant decrease in the speed of sound for the multi-phase flow compared to single-phase liquid or vapor flows. The relation is depicted in Figure 4 for the single-component fuel surrogate ethanol. The speed of sound shows a minimum below 25 m/s at a vapor fraction of 0.5 and a value significantly below 100 m/s for every point between 10% and 90% vapor fraction.

Figure 3. Series of high-speed images of cavitation within the transparent nozzle for ethanol at 10 MPa injection pressure, 0.1 MPa ambient pressure and 298 K fuel temperature.

Figure 4. Speed of sound for an ethanol fluid vapor mixture at 0.1 MPa as a function of its vapor fraction.

Figure 5. Setup for the X-ray multi-exposure images at the Argonne National Laboratory according to Wang et al.⁸

Since the ratio of injection pressure and ambient pressure is above the critical pressure ratio in GDI nozzles, the speed of sound is the velocity that will be reached in the narrowest flow area of the nozzle. For a cylindrical nozzle, the velocity could not increase downstream, causing the nozzle flow to choke at speed of sound conditions. Another possibility would be a venturi-nozzle-like effect due to the complex nozzle geometry, resulting in a supersonic flow. To determine which case is valid here, the flow speed within the nozzle has to be determined.

Nozzle outlet velocity and primary atomization

The nozzle outlet velocity can be used both for the description of the primary atomization and the estimation of flow conditions inside the nozzle. This is based on the continuum equation for the stationary case (injector needle fully opened, quasi-stationary flow), which is shown below with mass flow $\dot{m}$, velocity c and flow cross section A . Indices i and o mark internal flow and outlet conditions

$$\frac{d\dot{m}}{dt} = 0 \quad (2)$$

$$c_i \rho_i A_i = c_o \rho_o A_o \quad (3)$$

Assuming that the flow is following the spray axis and the cone angle is small, the radial expansion of the jet directly at the nozzle outlet can be neglected and the flow cross section can be assumed to be constant. Since even for high vapor fractions, the main part of the mass is transported in the liquid phase which can be assumed

to be incompressible, the difference in density can be neglected and the velocity inside the nozzle can be estimated to be the same as at the outlet.

Since the spray is very dense at the nozzle outlet, it is not accessible with conventional optical measurement techniques such as PDA/LDA or particle image velocimetry (PIV). Therefore, we used multi-exposure X-ray images to determine the velocity directly outside the nozzle. The measurements were carried out at the Advanced Photon Source (APS) of the Argonne National Laboratory (ANL; Figure 5). The APS electron storage ring was run in hybrid-singlet mode and each image was exposed to three to four X-ray bursts, which are approximately 150 ps long and 68 ns apart. The image was formed on a scintillator crystal and recorded by a complementary metal-oxide semiconductor (CMOS) high-speed camera at a frame rate of 67,890 fps. The camera is positioned orthogonal to the beam using an additional mirror. For each operating point, we recorded 10 image sequences.

Due to the multiple exposures, the resulting images show each spray structure several times. The movement of the structures is evaluated using a self-developed algorithm based on autocorrelation. After the background image is subtracted to improve contrast, the image is divided into 24 by 24 tiles and the cross-correlation of every tile and the original image is computed. To reduce computing time and avoid implausible displacements, the original image is cut to an area the structure can at a most reach assuming a maximum velocity of 125% of Bernoulli's velocity according to the fuel pressure. The resulting image shows several local maxima in the correlation coefficient, according to the number of exposures. The first and highest maximum thereby is representing the original position of the tile. To determine the velocity, the distance between the first and second maxima is divided by the time between two X-ray bursts. To make sure that only spray structures and no image artifacts are evaluated, a lowest acceptable correlation coefficient is defined. The optimal normalized correlation coefficient in our case turned out to be 0.2. As the X-ray beam generated by the synchrotron is limited in its size, during an injection, only a field of view of 2.4×2.4 mm can be recorded. To investigate bigger regions, the spray is divided into a grid which is rastered by moving the injection chamber relative to the beam. After the evaluation, a bigger image of the spray can be put together from the single images. Applying this algorithm to the multi-exposure images, gives us a velocity distribution within the first millimeters after the nozzle exit. Figure 6 schematically shows the evaluation procedure executed for every multiple exposed single-shot image.

To find the ideal number of tiles to achieve a good compromise between spatial resolution and precision, we carried out a parameter study as shown in Figure 7. To investigate the influence of the number of tiles on the result, the overall mean velocity of a constant time

Figure 6. Schematic description of the image evaluation algorithm dividing the background-corrected multiple exposed single-shot image into tiles and calculating the velocity from the displacement.

step ($1200\ \mu\text{s}$ after eSOI) was calculated and averaged over 10 consecutive injections. When calculating the mean velocity images, we only consider tiles where in at least 3 out of the 10 images, the minimum correlation coefficient condition is fulfilled. Figure 7 shows the mean velocity distribution in the first three millimeters after the nozzle exit. The images show that the number of tiles can be increased from 14 to 24 without getting implausible distributions or miss detections. When increasing the number to 28, miss detections start to occur whereby the resolution of the distribution does not increase significantly. For these reasons, a number of 24×24 tiles were chosen, also as a compromise between the spatial resolution and the computing time. The diagram in the lower right corner of the Figure 7 shows the average velocity of all tiles in the image versus the number of tiles. It clearly shows that there is no systematic influence of the number of tiles on the average velocity. The maximum deviation is $4\ \text{m/s}$ which is 1.7% of the mean value.

The resulting velocity distribution is shown in Figure 8. It represents a mean value of 10 injections and 11 consecutive images of each injection during the stationary phase (around $1200\ \mu\text{s}$ after the eSOI). The distribution clearly shows a radial velocity profile with high velocities on the spray axis, decreasing toward the edges of the spray. Also, along the spray axis, a small decrease in the velocities can be observed.

Evaluating the velocities along lines orthogonal to the spray axis at different distances to the nozzle exit leads to the diagram shown in Figure 9. The spray image on the left side of Figure 9 illustrates the position of the evaluated lines. The plot clearly shows profile relaxation and a development from a flat top profile over a super-Gaussian profile to a Gaussian-like Profile with increasing distance from the nozzle.

This profile relaxation is considered a major atomization mechanism. Leick¹⁶ shows a similar development of a jet based on theoretical considerations, which is shown in Figure 10.

Figure 7. Comparison of the resulting averaged velocity magnitude distributions in dependency of the number of tiles for 14, 24 and 28 tiles as well as the development of the overall average velocity magnitude of all tiles.

Figure 8. Velocity magnitude distribution for *n*-heptane at an injection pressure of 20 MPa and an ambient gas pressure of 0.1 MPa as intensity plot 1200 μ s after the electrical start of injection.

To compare the nozzle exit velocities from the X-ray measurements to velocities obtained from other measurement techniques such as LDA/PDA or Schlieren, the mean velocities are determined for three different fuel pressures. Therefore, the mean value of all non-zero elements from the first 2 mm after the nozzle exit is calculated and shown in Table 1.

Based on the velocity results and the assumption that the outlet velocity is the internal nozzle velocity as derived earlier, the vapor fraction inside the nozzle can be estimated. This can be derived from equation (3) as follows

Table 1. Mean velocities at the nozzle exit for different injection pressures.

Injection pressure (MPa)	10	20	24
Mean velocity (m/s)	162	207	232

$$\dot{m} = c_i \rho_i A_{eff} \quad (4)$$

$$\alpha = \frac{A_{vapor}}{A_{total}} \quad (5)$$

Assuming that $\rho_g \ll \rho_l$, we can assume that the whole mass flow is transported in liquid form and that the effective fuel density is nearly the same as the liquid fuel density. Hence follows an expression for α

$$\alpha = 1 - \frac{A_{eff}}{A_{total}} = 1 - \frac{\dot{m}}{c_i \rho_l A_{total}} \quad (6)$$

With the averaged velocity known from X-ray measurements, the injection rate is the last unknown variable. To determine the injection rates, measurements with a commercial Moehwald HDA measurement unit are performed. The measurement principle is based on the increase in pressure during injection, which can be

Figure 9. Average velocities for all images during the stationary phase (500–1500 μ s after eSOI) in dependency of the radial distance from the jet axis and the axial distance from the nozzle outlet.

Figure 10. Development of the velocity profile for a free jet from the nozzle outlet to the fully developed spray. According to with kind permission from Leick.¹⁶

converted to an increase in mass in a known volume using the speed of sound that is measured simultaneously and the following relation¹⁷

$$dm = \frac{dp}{c(p)^2} \quad (7)$$

For the investigated three-hole injector injected mass, injection rate and pressure drop in the fuel rail for 10 MPa injection pressure are given in Figure 11.

Inserting the single-hole flow rate of the injector, which is a third of the overall rate, the calculation of the vapor fraction for 10 MPa yields 33%. Compared to the images in Figure 3, this is a reasonable assumption. This means that the internal nozzle flow velocity is faster than the speed of sound in regions where a phase mixture is present (calculated based on equation (1)). Whether the flow is supersonic depends on the nature and distribution of the mixed areas.

Spray propagation downstream of the nozzle

To investigate the spray propagation of an isolated fuel jet and to eliminate influences from neighboring jets, single-hole nozzles are used. The spray propagation is visualized with high-speed Schlieren imaging, and

Figure 11. Injection rate, accumulated injected mass and pressure drop in the rail during injection for a three-hole injector and 10 MPa injection pressure.

droplet velocities and diameters are measured at 119 chosen positions on a plane through both injector and jet axis by means of two-dimensional (2D) LDA/PDA. The positions are depicted in Figure 12.

For each point, 30 injections are averaged with high signal rate due to the good optical accessibility of a single-jet spray. In combination with the Schlieren images that are recorded with a 20 kHz frequency and in 25 repetitions, this provides a comprehensive impression of the flow conditions in the downstream spray region.

From both measurement techniques, a velocity development on the spray axis can be obtained. Velocity information are both compared and extrapolated in order to compare them with the nozzle outlet velocities from X-ray structure tracking velocimetry and theoretical flow velocities from Bernoulli equation.

Spray velocity from high-speed Schlieren imaging. Schlieren imaging provides information about the macroscopic spray propagation. Velocities obtained in this approach are the derivation of the spray penetration depth over time. This means, it is actually only the velocity of the spray front and does not provide information about velocities in the spray center. For the application,

Figure 12. LDA/PDA measuring points marked in a Schlieren spray image with averaged velocities and droplet diameters for the respective time step after eSOI.

Figure 13. Penetration depth and resulting velocity from high-speed Schlieren for iso-octane at 15 MPa injection pressure, 0.1 MPa ambient pressure, 303 K fuel temperature and 298 K ambient temperature.

however, this is the most important velocity since it describes the geometrical spray propagation that determines component wetting and mixing. Figure 13 shows penetration depth and resulting velocity versus time after eSOI. To determine the velocity, a power law equation is fitted to the penetration depth curve and deviated with respect to time. The visible start of injection (vSOI) can be determined to be 328.5 μs after eSOI by the zero transition of the fitted power law curve. The initial velocity at injector opening at this point is calculated to be 183.1 m/s.

Droplet velocities and sizes from LDA/PDA. In contrast to Schlieren imaging, LDA/PDA provides velocities of single droplets and their respective diameters. That means microscopic spray parameters are accessible, but the measurement technique is limited to the liquid spray phase and, due to its punctual measurement volume,

the results depend strongly on measurement positions and statistics. To make the LDA/PDA results comparable to the nozzle outlet velocities, the maximum droplet velocity is calculated for each measurement point and the results are extrapolated along the spray axis. Since droplet acceleration outside the nozzle can be neglected in this case, the fastest droplets are those that reach the measurement point with the minimal interaction and therefore carry the information about the initial velocity. To avoid statistical errors, the maximum droplet velocity is defined as the average of the fastest 5% of the velocity distribution rather than the single-maximum value. However, to compare the Schlieren results, the mean velocity during the main spray event is evaluated. Figure 14 shows the maximum and mean droplet velocity distributions during the main spray event.

When we extract the maximum velocities on the spray axis and plot them against the distance to the nozzle, the nozzle outlet velocity can be estimated. This approach is shown in Figure 15. The velocity curve can be linearly fitted and extrapolated to an initial velocity of 207.6 m/s.

In addition, PDA provides information about the droplet sizes, that is, the atomization quality of the spray. The droplet size distributions found are shown for two measurement points on the jet axis in 30 and 50 mm nozzle distance. The respective histograms are shown in Figure 16 for the main spray event.

The distributions are normalized to their maximum value. They show good atomization quality for both nozzle distances, with a slight increase in diameter with increasing nozzle distance. This is due to multiple phenomena. The first is droplet evaporation, which mainly affects smaller droplets due to their higher surface/volume ratio, causing them to vanish and drop out of the statistics. The influence of this effect, however,

Figure 14. Spatial mean (left) and maximum (right) droplet velocity distribution during the main spray event for isooctane at 15 MPa injection pressure, 0.1 MPa ambient pressure, 303 K fuel temperature and 298 K ambient temperature.

Figure 15. Maximum droplet velocity distribution over nozzle distance during the main spray event for isooctane at 15 MPa injection pressure, 0.1 MPa ambient pressure, 303 K fuel temperature and 298 K ambient temperature.

Figure 16. Histograms of the droplet size distribution during the main spray event (accumulated during fully open needle operation) on the main spray axis at 30 and 50 mm nozzle distance for isooctane at 15 MPa injection pressure, 0.1 MPa ambient pressure, 303 K fuel temperature and 298 K ambient temperature.

increases with the evaporation rate and is small for the shown cold conditions. The second effect is droplet coalescence. Since droplet velocity and ambient gas velocity converge with increasing nozzle distance due to air entrainment and aerodynamic drag, the We number decreases. This means droplets are more likely to coalesce, causing the appearance of larger droplets. The third effect is the occurrence of measuring gaps in dense sprays regions. This affects small droplets first since their signal is weaker than the signal of large droplets, making them harder to detect. For the presented single-hole spray and the relatively large distances of 30 and 50 mm, however, the optical density of the spray is assumed to be sufficiently low. In contrast, two further aspects described by Jiang¹⁸ may play a role here. The first effect is a stronger deceleration of small droplets, again due to their surface/volume ratio, causing the droplets to drop out of the main spray event and therefore the detection period. This is especially significant for the rather short t_i of 1.5 ms used here. The second effect is the higher radial velocity component of small droplets, causing them to leave the spray center.¹⁸

Comparison of experimental and theoretical spray velocities

To compare and discuss the spray velocities that we determined with the different measurement techniques and evaluation procedures, a dimensionless representation is used. This way, even velocities measured for different injectors and injection conditions can be compared. In the present case, this is necessary because we were not able to carry out the respective results with the same nozzles, fuels and injection pressures. To this

Figure 17. Comparison of normalized nozzle exit velocities determined with PDA/LDA, Schlieren imaging and X-ray structure tracking velocimetry.

end, normalization to Bernoulli's outlet velocity is used. It results from the considerations of static and dynamic pressure of a fluid element in the nozzle under the assumption of an incompressible, liquid fluid and is shown in the following equations

$$p + \frac{\rho}{2} v^2 = \text{const.} \quad (8)$$

$$v_{\text{Bernoulli}} = \sqrt{\frac{2\Delta p}{\rho}} \quad (9)$$

In these equations, p is the static pressure, accordingly Δp is the pressure difference between fuel and ambient pressure and ρ is the fluid density. This means, normalization to $v_{\text{Bernoulli}}$ corrects for both, different fluids and different injection pressures. The resulting plot of dimensionless velocities is found in Figure 17.

PDA shows a very good agreement with Bernoulli's velocities since we only consider the maximum droplet velocity, and Bernoulli's law does not consider losses and non-ideal behavior. Schlieren velocity, however, is significantly lower. This is due to the fact that by deriving the penetration depth, only the spray front velocity can be determined. This means, it is the part of the spray that is affected by throttle effects at injector opening as well as the maximum aerodynamical drag during spray propagation. X-ray results are in the same order of magnitude as the Schlieren results. They do not consider throttle effects while opening since they are taken during the stationary phase but they are averaged over the whole nozzle diameter which means they also consider losses due to turbulence and friction.

Summary

Different approaches to measure and evaluate nozzle outlet velocities of modern GDI injectors were compared. The results show that there is an unneglectable amount of vapor in the nozzle even for cold conditions. The vapor fraction for cold conditions at 10 MPa injection pressure is calculated based on HDA and X-ray measurements and is around 33%. Consequently, the internal nozzle flow has to be treated as multi-phase flow, which means a significant decrease in speed of

sound. This decrease in the speed of sound explains the known choked flow in GDI injectors (the counter-pressure does not influence the mass flow). This is especially remarkable since the nozzle outlet velocity still shows a very good agreement with Bernoulli's velocity, whose approach, however, is only valid for incompressible flows. A possible explanation is a very clear spatial separation of the liquid and vapor phase which allows for high total vapor fractions, while the liquid fraction can still be treated as approximately incompressible.

The maximum nozzle outlet velocities are found to be close to Bernoulli velocity and are in good agreement with the maximum droplet velocity inside the spray. The mean nozzle outlet velocity, however, is lower as the X-ray measurements show. The initial spray front velocity, which can be derived from macroscopic imaging measurement techniques, is comparable to the X-ray results.

For all velocities, it has to be taken into account that the mean velocity for single droplets and spray structures is the average length of the velocity vector in the measurement plane. In LDA, one velocity component in direction of the spray penetration and one component normal to the spray axis are considered, while deriving it from the penetration depth only provides information about the axial velocity of the spray.

Overall, the small difference between extrapolated spray front velocity and measured nozzle outlet velocity shows that the spray front velocity close to the nozzle is good measure for the initial spray momentum.

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