Effects of ambient conditions and nozzle design on the velocity of clustered Diesel jets

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Abstract The measurement of droplet velocities in Diesel sprays close to the nozzle is important because of the complexity of in-nozzle flow, spray break-up and evaporation. However, the measurement of droplet velocities in the dense region of Diesel sprays is very difficult or impossible by means of widely used laser diagnostic techniques, in particular under engine-like high-pressure and high-temperature conditions. The limitations of Phase Doppler Anemometry (PDA) and Particle Image Velocimetry (PIV) prevent the application to the ultra-dense region of the spray. It was demonstrated, that these problems can be greatly reduced by the Laser Flow Tagging (LFT) technique. It was also demonstrated recently that LFT measurements can be conducted in clustered Diesel jets with improved spatial resolution and increased number of simultaneous measurements in the near-nozzle region.

In the present work, the nozzle design, the temperature and pressure of the ambient air, and the fuel rail pressure are varied, in order to investigate the influence on the near-nozzle jet velocity and the underlying physical mechanisms.

1. Introduction

The realization of improved Diesel engine combustion in terms of fuel consumption and emission reduction requires a deeper understanding of the structure of Diesel sprays, which directly affects mixture formation, combustion and emission formation. Currently there is a certain lack of experimental data on the spray structure, in particular in the vicinity of the nozzle. This is basically caused by the very high droplet density, which leads to severe problems for most optical techniques, such as PIV and PDA, due to strong light scattering and beam deflection. However, it was demonstrated previously that droplet velocity measurements in such dense sprays can be achieved by the LFT technique [1,2]. Currently this is the most suitable diagnostic to yield droplet velocity data even in the ultra-dense region of Diesel sprays under realistic high-pressure and high-temperature conditions [1,2]. Recently the spatial resolution of multi-point velocimetry using LFT was improved significantly, in order to be able to study the velocity field close to the nozzle in detail [3]. It was another aim of recent work to demonstrate the applicability of a modified LFT set-up that requires optical access to the spray from only one side, so that conventional multi-hole nozzles and cluster nozzles can be investigated [3]. This was not possible by the previous LFT technique [1,2], which required optical access from at least two sides, because measurements in the concerning spray were obscured by neighboring jets.

Cluster nozzles, which provide closely-spaced, strongly-interacting sprays, are currently being developed for Diesel engines with reduced NOx and soot emissions, as described in [4-6] and references therein. Experimental results show that spray instabilities may arise for cluster nozzles.
with more than one orifice circle [4,5]. Accordingly, 3D-CFD simulations demonstrate that the fluid flow inside such nozzles is very complex and that it may be extremely sensitive to the geometric boundary conditions [6]. Thus, it is particularly important to measure the droplet velocity very close to such nozzles under approximately realistic conditions as demonstrated in the present paper.

The principle of LFT for determination of droplet velocities in a single Diesel spray is shown in Fig. 1. In a first step, the so called “write” process, a number of droplet groups are tagged. Their displacement, $\Delta x$ is then detected after a delay, $\Delta t$, in a second step, the “read” process, yielding the velocity. In order to avoid ambiguities and to minimize errors in image processing, it is essential to create a distinct structure in the flow during the “write” process. For this purpose usually pulsed laser beams are used, tagging the flow by an appropriate optical set-up [1].

In “one-dimensional” flows (only one predominant velocity component) it may be adequate to tag the fluid with one or more parallel laser beams. This is the case in the present application. A number of related flow tagging techniques in other applications are briefly described elsewhere [7].

To our knowledge, the first flow tagging measurements in sprays were presented in [8,9]. The first applications of LFT to Diesel sprays were presented in [1]. Droplet velocity measurements were conducted under conditions of elevated pressure and temperature in [2]. For this purpose the model fuel was doped with a phosphorescent tracer, which was excited by a number of focused laser beams and then probed twice with a delay of $\Delta t$ using a double-frame ICCD.

2. Experimental

A modern Common-Rail piezo injector equipped with different nozzles is installed in a high-pressure and high-temperature chamber that yields engine-like boundary conditions [2]. Two cluster nozzles and a reference nozzle are investigated as described in Tab. 1. The cluster nozzles generate three jet clusters with two jets each. The nozzle holes in each cluster of nozzle #1 are parallel, whereas they are convergent (with an angle of 4°) in the case of nozzle #2. Nozzle #3 is a rather conventional 3-hole nozzle with larger nozzle hole diameter. As model fuel in this study n-decane (purity > 99%, Merck Schuchard OHG) is used. A schematic illustration of the set-up is shown in Fig. 2 a). One of the fuel jets, or jet clusters respectively, is illuminated by the laser through the observation window. The laser beam is split into five horizontal sheets by five small cylindrical lenses, each with a height of 1 mm and a focal length of 300 mm. Thus, a beam profile of 0.16 mm x 10 mm is obtained in the probe volume. An image-intensified double-frame ICCD-camera (Nanostar, LaVision GmbH) equipped with a 180 mm f/2.8 lens (Nikon) is used.

<table>
<thead>
<tr>
<th>nozzle</th>
<th>Type</th>
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<th>cluster angle</th>
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<td>99 µm</td>
<td>4°</td>
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<tr>
<td>#3</td>
<td>Reference</td>
<td>3</td>
<td>204 µm</td>
<td>--</td>
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</table>
The phosphorescent fuel tracer is the lanthanide-chelate complex terbium(III) tris(2,2,6,6-tetramethyl-3,5-heptanedionate) (Tb:(tmhd)$_3$, 98%, Aldrich). The lanthanide-chelate is dissolved in n-decane with a concentration of 5 x $10^{-3}$ mol/l. For excitation a pulsed Nd:YAG laser (Spectra Physics Laser GCR 130) with a fourth harmonic generator is used at 266 nm. The spray is investigated for different fuel rail pressures, ambient pressures and temperatures as described below. The injector energizing time is set to 450 µs. The exposure time, $g$, of the camera is 1.0 µs or 0.5 µs, respectively, for each frame. The images are acquired at 500 ns after the laser pulse with a delay between the two frames of 1 µs up to 3 µs. The measurement time after energizing the injector, $t_{aei}$, is varied. Fuel injection actually starts at a $t_{aei}$ of about 230 µs. One of the jet clusters of cluster nozzle #1 is visualized by shadowgraphy as shown in Fig. 2 b). The nozzle tip is located close to the lower left corner of the image.

A typical raw ICCD image pair averaged over 24 single-shot measurements (one measurement per injection) is shown in Fig. 3. Nozzle #2 is investigated in this case. The delay, $\Delta t$, between the two images (exposure time $g$ = 0.5 µs) is 1.5 µs. Fig. 3 shows that five droplet groups in each of the two jets are tagged by the laser beams. The signal intensities in the second image are lower basically due to the phosphorescence decay. It can be seen that the droplet groups moved downstream in the second frame. Vertical intensity profiles from the left jet in Fig. 3, which are averaged over the full width of the left spray (according to Fig. 2 b)), are presented in Fig. 4 a) and b) as an example. They show the three tag lines which are close to the nozzle.

![Figure 1: Principle of Laser Flow Tagging applied to a single fuel jet.](image1)

![Figure 2: a) Set-up of the flow tagging experiments (adopted from [3]). b) The investigated jet cluster of nozzle #1 visualized by shadowgraphy ($p_{rail}$ = 1200 bar, $p_A$ = 18.6 bar, $T_A$ = 300 K, $t_{aei}$ = 275 µs; adopted from [3]).](image2)
Droplet velocities are determined by fitting Voigt peak functions to the phosphorescence intensity profiles of the single-shot, i.e., quasi-instantaneous, measurements. These are also shown after averaging in Fig. 4 a) and b). The velocities are calculated from the displacement of the Voigt peak functions, \( \Delta x \), and the delay, \( \Delta t \), according to \( v = \Delta x / \Delta t \). Fig. 4 shows that six velocity measurements can be conducted in the near-nozzle region, i.e., \( x < 4 \text{ mm} \), of these clustered sprays of nozzle #2 simultaneously. Thus, the highly-resolved velocity profiles of the two sprays can be measured and compared precisely in this region, despite of spray instabilities and possible drifting of the injection system or the conditions in the vessel. However, high spatial resolution with larger tag line distance can also be achieved for ensemble-averaged measurements if long-time fluctuations of the spray are small by variation of the tag line positions. This technique is applied in the case of nozzle #1. The tag line distance close to the nozzle is 2 mm in this case, and two measurements with different tag line positions are conducted. Thus, the resulting velocity profiles, which are shown below, contain eight averaged velocity measurements at \( x \leq 4 \text{ mm} \). Compared to previous work [2], the number of simultaneous velocity measurements in this near-nozzle region of the example given in Fig. 3 is increased by a factor of three, and the spatial resolution, i.e., the tag line distance is improved by a factor of four in the case of the measurements at \( x < 2 \text{ mm} \). However, this spatial resolution of 1 mm can not be achieved further downstream due to stronger tag line broadening caused by multiple light scattering. Thus, a tag line distance of 2 mm is chosen at \( x \approx 4 \text{ mm} \) as shown in Fig. 3. Moreover, Fig. 3 shows that a tag line distance of 4 mm is used at \( x > 4 \text{ mm} \) for the same reason. These measurements at \( x > 4 \text{ mm} \) are not included in Fig. 5-9, because they can not be conducted simultaneously to the measurements at \( x < 4 \text{ mm} \), since \( \Delta t \) must be chosen different for both groups of tag lines [2]. Lower velocities and higher tag line widths require higher \( \Delta t \) at larger \( x \), in order to optimize the precision. In addition, the individual jets of a cluster can not be distinguished at \( x > 4 \text{ mm} \) due to interaction of the jets as shown in Fig. 3. Thus, the measurements at \( x > 4 \text{ mm} \) are not shown in the plots presented below.

Figure 3: Typical raw image pair (\( \Delta t = 1.5 \mu s, p_{\text{rail}} = 1200 \text{ bar}, p_A = 18.6 \text{ bar} \) and \( T_A = 300 \text{ K} \)); The two clustered jets are convergent with an angle of 4° (adopted from [3]).
3. Results

The results of the measurement shown in Fig. 3 and 4 are presented in Fig. 5. In addition, corresponding results at higher ambient air pressure in the vessel ($T_A = \text{const}$.) are given in the same diagram. The data show that the jet velocities at a nozzle distance, $x$, of about 1 mm depend only slightly on the ambient air density. This indicates that the deceleration of the jets is small at $x < 1$ mm, in particular at low ambient density. This is also corroborated by the similarity of the velocities at $x \approx 1$ mm and 2 mm. The jet deceleration was found to be small at $x < 1$ mm when the pressure difference between fuel rail and ambient air was high for a conventional nozzle in Ref. [10]. Furthermore, Fig. 5 shows that the left jet is faster than the right one in the present case. This is generally found for both cluster nozzles. Accordingly, the penetration lengths of the two jets are different as shown in Fig. 2 b). This can be explained by the complex fluid flow inside the nozzle, as demonstrated in Ref. [6]. The error bars in Fig. 5-9 correspond to the standard deviation of the single-shot measurements.

The error bars at a nozzle distance, $x$, of about 1 mm of the measurements at $p_A = 18.6$ bar in Fig. 5 demonstrate, that the precision of these single-shot measurements is given by less than 5% relative error, although they suffer from shot noise [2]. The corresponding measurement error was found to be of the same order of magnitude in conventional Diesel jets in [1, 2]. Furthermore, Fig. 5 shows that the error bars generally increase with increasing nozzle distance. This can be explained basically by the lower droplet velocities and the stronger influence of multiple light scattering at larger nozzle distance [2]. Multiple light scattering leads to larger tag line widths, as shown in Fig. 4. Lower droplet velocities lead to smaller tag line displacements. Thus, the non-vanishing tag line width becomes more important, and this leads to larger errors. However, Fig. 5 also shows that the shot-to-shot fluctuations are higher in the left jet than in the right jet (at $p_A = 18.6$ bar). This demonstrates that the variations in the droplet velocities of the individual spray pulses also contribute significantly to the error bars given in Fig. 5. Obviously, these variations are higher in the left spray at 18.6 bar. In contrast, it was found that such spray fluctuations are rather negligible in the case of a conventional nozzle [2]. Accordingly, other experimental results indicated that strong spray instabilities may occur for such cluster nozzles as mentioned in the Introduction [4, 5].
The precision of the ensemble-averaged measurements in Fig. 5 is better than the error bars basically because photon statistical noise is reduced by averaging [2]. For example, the precision of comparable averaged measurements was determined to be about 2.5% at \( x \approx 1 \text{ mm} \), and 5% at \( x \approx 4.5 \text{ mm} \), respectively, in Ref. [2]. In the present case the measurement precision is generally slightly lower, because of faster dispersion of the tagged droplet groups. This leads to faster tag line broadening, which can be observed when Fig. 3 is compared to the corresponding results of conventional nozzles [2]. Faster dispersion of the tagged droplet groups also indicates that the hydrodynamic turbulence or the radial velocity gradients are higher in the sprays of these cluster nozzles.

Typical velocity data of the three investigated nozzles for \( t_{\text{aei}} = 400 \mu\text{s} \) and \( 600 \mu\text{s} \) are presented in Fig. 6 and 7, respectively. The similarity of the results of the two cluster nozzles indicates that quasi-steady spray conditions are reached at \( t_{\text{aei}} = 600 \mu\text{s} \). In contrast, the results depend significantly on \( t_{\text{aei}} \) in the case of the reference nozzle. Consequently, the sprays generated by the reference nozzle are only approximately quasi-steady at \( t_{\text{aei}} = 600 \mu\text{s} \). Furthermore, the results of the two cluster nozzles in Fig. 6 and 7 are only slightly different. This implies that the difference in the angle of the interacting jets in each cluster does not significantly affect the fluid flow close to the nozzles.

Fig. 7 also shows that the deceleration of the jets generated by the cluster nozzles is again relatively small close to the nozzles \((x < 2 \text{ mm})\) in particular under quasi-steady conditions (it should be noted that the fuel rail pressure is significantly lower in these measurements in comparison to the data shown in Fig. 5). This implies that the quasi-steady nozzle exit velocities, \( v_0 \), (at \( x = 0 \)) can be determined approximately by the measurements at \( x \approx 1 \text{ mm} \) at least for the cluster nozzles. It turns out that the exit velocity of these nozzles is generally significantly lower than the result of a Bernoulli estimation \( v_B \). In contrast, \( v_0 \) was found to be very similar to \( v_B \) for a conventional nozzle in [2]. The relatively low \( v_0 \) of the cluster nozzles can be explained by the nozzle design [6]. Many spray models assume that \( v_0 \) is equal to \( v_B \) [11,12].
also indicated by particularly fast broadening of the tag lines, which is found in the concerning unsteady phase of injection for conventional nozzles [13]. Relatively strong liquid-gas interaction is nozzle as compared to the cluster nozzles. This unsteady behavior of the reference nozzle can be explained by stronger liquid-gas interaction caused by a larger spray cone angle, which is observed in the corresponding images. Larger spray cone angles were also observed previously in the early, unsteady phase of injection for conventional nozzles [13]. Relatively strong liquid-gas interaction is also indicated by particularly fast broadening of the tag lines, which is found in the concerning measurement of the reference nozzle. Fig. 6 shows that at \( t_{\text{aci}} = 400 \, \mu s \) relatively high pulse-to-pulse fluctuations occur for the reference nozzle. In contrast, the low pulse-to-pulse fluctuations and tag line broadening of this nozzle at \( t_{\text{aci}} = 600 \, \mu s \) (see Fig. 7), indicate that approximately quasi-steady spray conditions are reached in this case as mentioned above.

**Figure 6:** Results of the velocity measurements for the investigated sprays of nozzle #1-#3. The error bars correspond to the standard deviation of the single-shot measurements. The jets are named according to Fig. 2 b); \( p_{\text{rail}} = 800 \, \text{bar}, \, t_{\text{aci}} = 400 \, \mu s, \, T_A = 300 \, \text{K}, \, p_A = 18.6 \, \text{bar}. \)

**Figure 7:** Results of the velocity measurements for the investigated sprays of nozzle #1-#3. The error bars correspond to the standard deviation of the single-shot measurements. The jets are named according to Fig. 2 b); \( p_{\text{rail}} = 800 \, \text{bar}, \, t_{\text{aci}} = 600 \, \mu s, \, T_A = 300 \, \text{K}, \, p_A = 18.6 \, \text{bar}. \)

Fig. 6 also demonstrates that droplet deceleration close to the nozzle is stronger for the reference nozzle as compared to the cluster nozzles. This unsteady behavior of the reference nozzle can be explained by stronger liquid-gas interaction caused by a larger spray cone angle, which is observed in the corresponding images. Larger spray cone angles were also observed previously in the early, unsteady phase of injection for conventional nozzles [13]. Relatively strong liquid-gas interaction is also indicated by particularly fast broadening of the tag lines, which is found in the concerning measurement of the reference nozzle. Fig. 6 shows that at \( t_{\text{aci}} = 400 \, \mu s \) relatively high pulse-to-pulse fluctuations occur for the reference nozzle. In contrast, the low pulse-to-pulse fluctuations and tag line broadening of this nozzle at \( t_{\text{aci}} = 600 \, \mu s \) (see Fig. 7), indicate that approximately quasi-steady spray conditions are reached in this case as mentioned above.
Figure 8: Results of the velocity measurements for the investigated sprays of nozzle #1-#3. The error bars correspond to the standard deviation of the single-shot measurements. The jets are named according to Fig. 2 b); $p_{\text{rail}} = 1200$ bar, $t_{\text{sei}} = 600$ µs, $T_A = 300$ K, $p_A = 18.6$ bar.

Figure 9: Results of the velocity measurements for the two investigated sprays of nozzle #1 for two different $T_A$ at same air density, $\rho_A$. The error bars correspond to the standard deviation of the single-shot measurements. The jets are named according to Fig. 2 b); $p_{\text{rail}} = 800$ bar, $t_{\text{sei}} = 600$ µs.

Furthermore, Fig. 7 and Fig. 8 show that the droplet deceleration, $\Delta v/\Delta x$, in the range $1.5 \text{ mm} < x < 4 \text{ mm}$ decreases with increasing fuel rail pressure for both cluster nozzles. This is also found at higher ambient air temperature ($T_A = 800$ K, $p_A = 50$ bar). The observed phenomenon indicates that liquid-gas interaction is weaker at higher $p_{\text{rail}}$. Weaker liquid-gas interaction may be explained by retarded jet break-up at higher $p_{\text{rail}}$ as indicated by the velocity profiles. Accordingly, the gas velocity in the dense region of conventional Diesel sprays was found to be nearly independent of the fuel rail pressure in Ref. [10]. However, Fig. 8 shows that relatively strong jet deceleration is also found at $x = 2$ mm for the reference nozzle at higher fuel rail pressure (1200 bar). This can not be explained up to now.

The temperature effects on the jet velocity profiles of cluster nozzle #1 at constant air density, $\rho_A$, are illustrated in Fig. 9. Approximately engine-like ambient air conditions are reached in the high-
temperature measurements at $T_A = 800$ K and $p_A = 50$ bar. Obviously, the droplet deceleration decreases with increasing ambient temperature in the investigated $x$ range. This unexpected phenomenon is also found under all investigated conditions of $t_{aei}$ and $p_{rail}$. It may be explained by retarded jet break-up at higher temperature.

Additional measurements are conducted at $x \approx 6$ mm for the cluster nozzles, which are not included in the data given in Fig. 5-9, as mentioned above, in order to investigate the jet velocity further downstream. For example, jet velocities of about 120 m/s (at $t_{aei} = 400$ µs) and 160 m/s (at $t_{aei} = 600$ µs) are found for nozzle #2 at $x \approx 6$ mm, $p_A = 18.6$ bar, $T_A = 300$ K and $p_{rail} = 800$ bar. The corresponding results at $x < 4$ mm are given in Fig. 6 and 7. In general, it can be concluded that the velocities at $x \approx 6$ mm are only slightly lower than at $x \approx 4$ mm. Thus, strong droplet deceleration in the sprays of the cluster nozzles occurs only in the range $1 \text{ mm} < x < 4$ mm. Accordingly, the droplet velocities were found to be approximately constant downstream from a certain location in the sprays of a conventional nozzle in Ref. [7].

4. Summary and Conclusions

Multi-point velocity measurements are conducted in the near-nozzle region of two common-rail cluster nozzles and a reference nozzle by using a recently developed LFT set-up that provides improved spatial resolution. The ambient conditions and the fuel rail pressure are varied. The conclusions are given in the following.

1. The jet velocities of the cluster nozzles are generally very similar, i. e., the different angle between the jets in each cluster does not affect the velocities significantly in the near-nozzle region.
2. The velocities of the reference nozzle under approximately quasi-steady conditions are similar to the corresponding results of the cluster nozzles at a fuel rail pressure of 800 bar, but different velocity profiles are found at 1200 bar.
3. The reference nozzle reaches quasi-steady spray conditions later (after energizing the injector) than the cluster nozzles due to the nozzle design and different hole diameter.
4. Significantly lower velocities and stronger deceleration are observed for the reference nozzle under unsteady conditions in comparison to quasi-steady conditions. This may be explained by the spray cone angle.
5. The velocities and pulse-to-pulse variability are generally different for the two jets in a cluster of both cluster nozzles due to the nozzle design.
6. The pulse-to-pulse variability in the velocity is generally larger for the present nozzles compared to a conventional nozzle investigated previously [2]. This can be explained by enhanced hydrodynamic turbulence caused by the present nozzle design.
7. The nozzle exit velocity is significantly lower than the result of a Bernoulli estimation for both cluster nozzles due to the nozzle design.
8. Strong droplet deceleration is observed only in the range $2 \text{ mm} < x < 3$ mm for both cluster nozzles, i. e., deceleration is weak in the other regions.
9. The deceleration in the range $1.5 \text{ mm} < x < 4$ mm decreases with increasing fuel rail pressure for the cluster nozzles, due to changing liquid-gas interaction.
10. The droplet deceleration in the range $1 \text{ mm} < x < 4$ mm decreases with increasing temperature of the ambient air (at constant air density) for cluster nozzle #1. This may be explained by retarded jet break-up at higher temperature.
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References


