

Experimental Investigation of the Interaction of Multiple GDI Injections using Laser Diagnostics

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ABSTRACT

In present GDI engines, multiple injection strategies are often employed for engine cold start mixture formation. In the future, these strategies may also be used to control the combustion process, and to prevent misfiring or high emission levels. While the processes occurring during individual injections of GDI injectors have been investigated by a number of researchers, this paper concentrates on the interactions of multiple injection events. Even though multiple injection strategies are already applied in most GDI engines, the impact of the first injection event on the second injection event has not been analyzed in detail yet.

Different optical measurement techniques are used in order to investigate the interaction of the two closely timed injection events, as well as the effect of dwell time and the in-cylinder conditions. The injector investigated is a GDI piezo injector with an outwardly opening needle. The laser diagnostics applied include measurement of the spray injection velocity profile close to the nozzle exit by Laser Correlation Velocimetry (LCV) and the droplet velocities at nozzle distances between 10 to 15 mm by Phase Doppler Anemometry (PDA). The penetration length and the overall spray shape, including the spray fingers and toroidal vortices, are compared using light scattering and laser light sheet measurements. A comparison of the spray structures shows that as well in-cylinder temperature and pressure as the dwell time have a significant impact on the intensity of the interaction.

INTRODUCTION

In order to reduce emissions and to prevent the risk of combustion instabilities such as misfiring, the combustion process of a GDI engine must be controlled. One approach to control the combustion process is the application of multiple injections within one cycle.

The investigated GDI piezo injector with its outwardly opening needle has the capability to inject three times within one cycle [1] using very short dwell times between two injection events [2]. Previous investigations have been made to examine one single injection only. Therefore the general spray shape is already known. The spray consists of a hollow cone with a toroidal vortex (see Figure 1); the hollow cone is separated into a multitude of droplet strings (see Figure 2), which are mainly caused by the nozzle flow [2, 3].

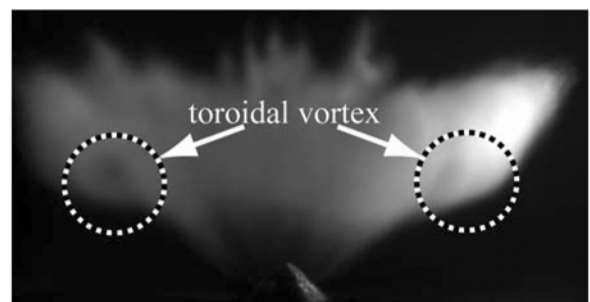


Figure 1. Typical spray image with toroidal vortex

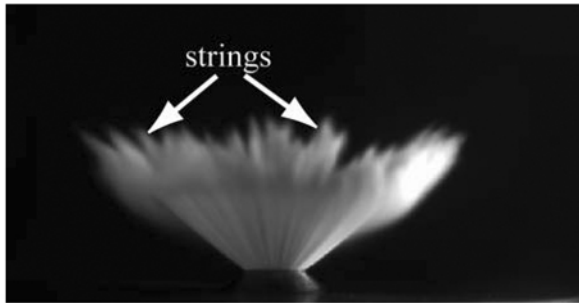


Figure 2. Typical spray image with strings

During the trigger time-point an ignitable mixture has to be present at the spark plug. Since the toroidal vortex consists of an ignitable mixture, the preferred position of the spark plug is within this vortex [2, 4]. Consequently, the position of the toroidal vortex is subject of the investigations summarized here.

While the processes occurring during an individual injection have been investigated by different researchers in the past, the interactive processes governing multiple injections have only been examined to a small extent. In contrast to the first injection, the second spray is injected into different in-cylinder conditions with a temperature, velocity and concentration field induced by the first injection. The different ambient conditions may have an impact on the second spray and may change the mixture process of the second injection event. In some cases, even the nozzle exit conditions may have changed by the first injection event, with significant influence on the second injection.

MAIN GOAL OF THE INVESTIGATION

Before multiple injections may be used to control the combustion process, one very important question has to be answered: What is the difference between the second injection and the first injection when the same boundary conditions apply to both injection events?

Therefore, the experimental studies cover single injections and double injections with different dwell times as well as variations in in-cylinder pressure and temperature. The measurement schedule is adjusted to the different measurement techniques applied and is therefore listed separately in each description of the experimental setup. For obtaining information about the spray shape backlight and laser light sheet visualizations have been applied. Determination of the spray exit velocity and the velocities of the spray droplets has been achieved by Laser Correlation Velocimetry (LCV) and Phase Doppler Anemometry (PDA).

GENERAL EXPERIMENTAL SETUP

The measurements under pressurized conditions are made in a pressurized chamber (see Figure 3 and Figure 4). For this, the injector is mounted in the chamber head, injecting from top to bottom. The air is pressurized and heated to the desired conditions, and is entering the chamber through the air inlets located at the sides of the pressure chamber. The airflow has a velocity of approximate 0.1 m/s, which is sufficient to purge the chamber without disturbing the spray. Three quartz glass windows allow optical access for the different measurement techniques applied.

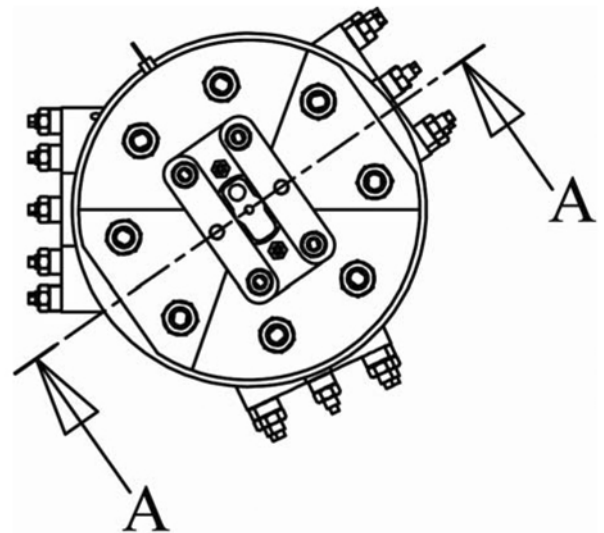


Figure 3. Pressurized chamber, top view

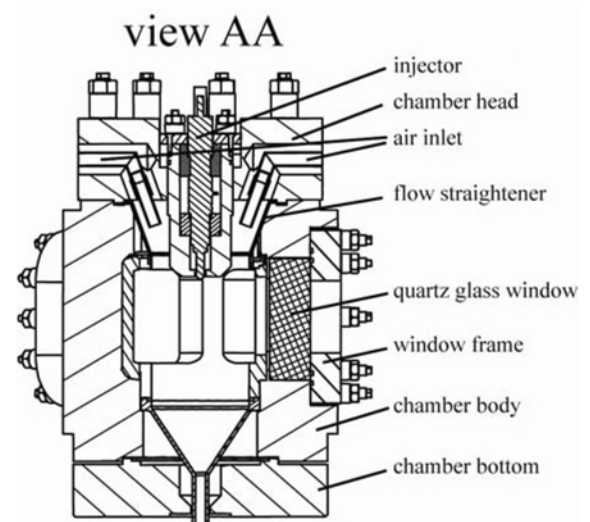


Figure 4. Pressurized chamber at cutting plane AA

The injection system used to feed the injector is a pressurized accumulator delivering an injection pressure of 10 MPa. The fuel pressure entering the injector is measured. The fuel

injected is a mixture of 95 vol-% iso-octane and 5 vol-% n-heptane. The injector is energized only for full needle lift using a modified control unit triggered with a TTL signal. The length of the injection event is defined by the length of the TTL signal. For both injection events, the TTL signal duration was 0.3 ms which, for atmospheric conditions, results in an injected fuel mass of 8 mg. The trigger scheme for the double injection is illustrated in Figure 5. The previous mentioned dwell time is called delay in this paper.

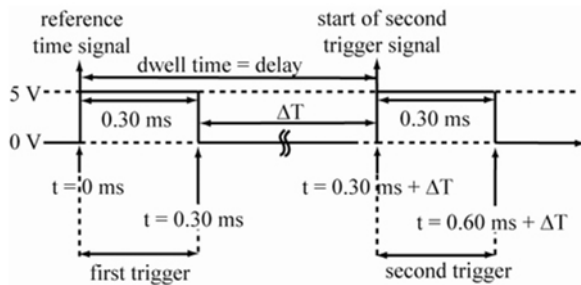


Figure 5. Trigger scheme of double injection

VISUALIZATION SETUP

Three different setups are applied for the visualization measurements. At atmospheric conditions, the test rig is set up with a backlight, as shown from side view in Figure 6. The backlight is used since the illumination is very evenly. At chamber conditions, two different setups are used, either with a stroboscope for scattering images or with a laser light sheet of an Nd:YAG-laser instead of the stroboscope (see Figure 7) for a cut view of the spray. For the chamber conditions the stroboscope is used instead of the backlight because of its stronger light intensity. But therefore the illumination is non-uniform over the light screen. This property does not matter for the scattering technique applied at chamber conditions but is undesirable for the backlit visualization. Both setups are purged with air as described before. Thus, the only technical difference between the visualization measurements is the light source employed and the arrangement of CCD-camera and light source.

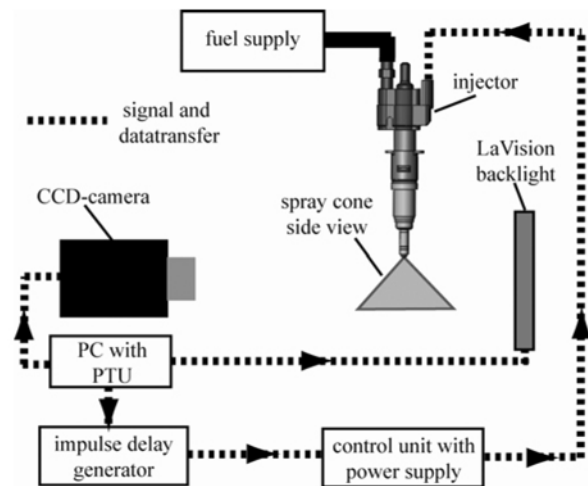


Figure 6. Atmospheric test rig for visualization

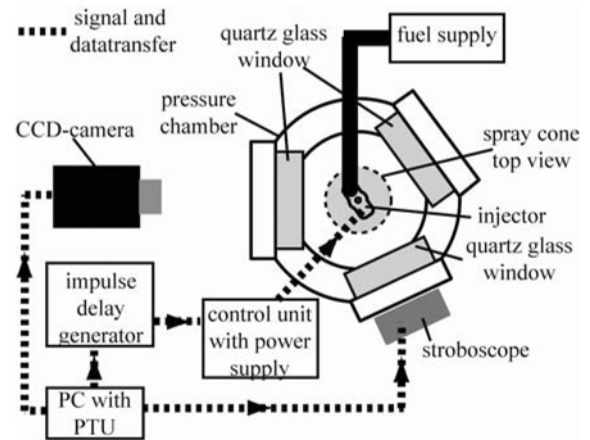


Figure 7. Chamber setup - top view

The parameters varied for the visualization measurements investigating double injection are listed in Table 1. The single injection is investigated for even more conditions applying the listed techniques. Due to the high effort needed to investigate all different delay of the double injection, the measurement programm for double injection is reduced. For both the measurements with backlight and stroboscope, different delays of 0.6 ms, 0.7 ms, 0.9 ms, 1.1 ms, 1.3 ms 1.5 ms, 2.0 ms, 2.5 ms and 3.0 ms are considered, and additionally delays of 3.5 ms and 4.0 ms for the stroboscope measurements only. With laser light sheet only delays of 0.7 ms, 0.9 ms and 1.1 ms are investigated.

Table 1. Measurement parameter listing for different visualization techniques investigating double injection (B = backlight, S = stroboscope, L = laser lightsheet)

		Temperature conditions		
		300 K	500 K	600 K
Pressure conditions	0.1 MPa	B		
	0.3 MPa	S		
	0.5 MPa	S, L	S	S, L
	1.0 MPa		S	L

For all combinations of chamber conditions and injection sequences, at least 20 images are taken for each time step. The time difference between the injection sequences is 2 s. An automated MATLAB script is used to extract information about the penetration length of the spray calculating the mean penetration length and the standard deviation of the penetration length. The penetration length is determined as the axial position that has only been exceeded by 0.5 % of the overall spray area at the specific time step (see Figure 8). Additionally, picture series are compiled resulting in an average picture based on 20 single injection events of each time step (see Figure 10). Enabling an easy comparison between pictures and resulting graphs, the original images are turned by 180° resulting in a spray which propagates from the bottom to the top.

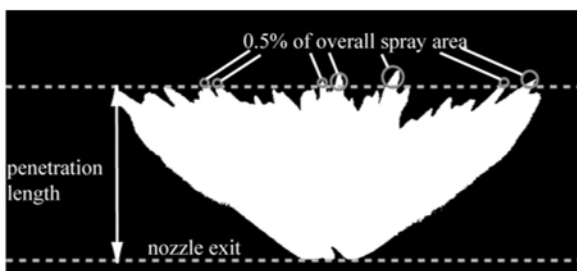


Figure 8. Definition of the penetration length

VISUALIZATION RESULTS

Based on the visualization measurements the injection process can be divided into two intervals. The first interval is from 0.14 ms to 0.55 ms after energizing the injector. During this time interval the nozzle is opening and the hollow cone consists of many strings. Even the averaged result in a clear image with no variations. This is an evidence of a very good reproducibility of the spray from one cycle to the next. The second interval starts when the toroidal vortex becomes

visible (at around 0.6 ms) until the end of the recording time. During this time interval the nozzle is closing and therefore the interaction with the gas phase and evaporation become more important. An exemplary image series for the operating point 0.5 MPa and 600 K is shown in Figure 10. The corresponding plot of the penetration length for the image series for 0.5 MPa and 600 K is given in Figure 9. The higher standard deviation for 1.3 ms to 1.5 ms results from the evaporation of the spray.

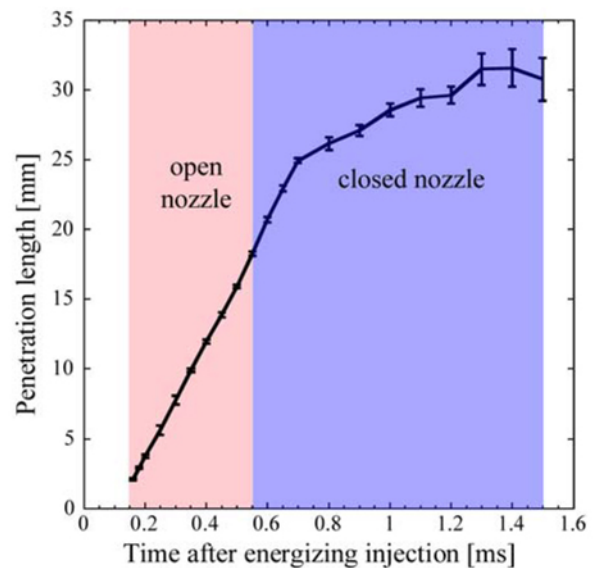


Figure 9. Penetration length for 0.5 MPa and 600 K

When evaluating the influence of the first injection on the penetration and string structure of the second injection, both sprays have to be analyzed separately. The separation is possible only before both sprays have merged. Figure 11 shows an averaged image for the double injection at 0.7 ms after energizing the second injection. At this time the nozzle is closing again and the separation of the two injection events becomes very difficult. Therefore the penetration length of the second injection event can only be evaluated until approximately 0.8 ms after the second event.

<figure 10 here>

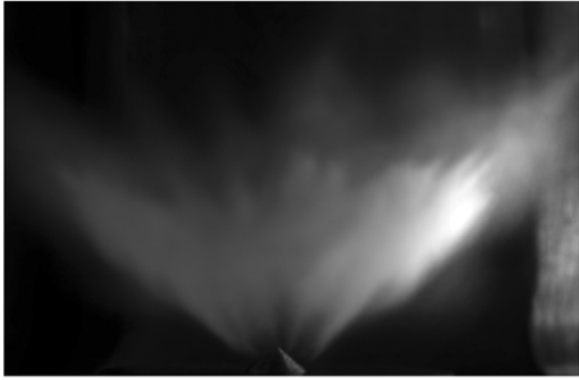


Figure 11. Double injection event (time delay 1.1 ms) at 0.5 MPa chamber pressures and 300 K chamber temperature. Image recorded at 0.7 ms after energizing for the second time

The investigations of the spray structure show a distinct string pattern for the double injection at chamber pressures of 0.1 MPa and 0.3 MPa (see comparison in [Figure 12](#)), consisting of thin string with long penetration and thick strings with short penetration, which appear at the same angular position. The thinner strings with higher penetration lengths can only be observed from 0.2 ms to 0.35 ms after start of the second event. When increasing the delay between the injection events or raising the chamber pressure to 0.3 MPa, the optically thinner strings decrease in length and become hard to detect. At an ambient pressure of 0.5 MPa, the thin strings cannot be observed anymore. The origin of the optically thinner strings cannot be explained as there is no information on the inner nozzle geometry available. However, Befrui [5] already mentions that the strings result from irregular wetting of the inner surface of the nozzle. Therefore, one reason for the optical thinner strings may be that the surface is already wetted by the first injection event at the point of time the second energizing starts. When increasing the delay (comparing [Figure 12](#) middle vs. bottom), the optical thinner strings decrease in length which may be caused by a decrease of wetting from the first injection event. If the chamber pressure is increased, the resistance of the air within the chamber grows as well, and the thinner strings are suppressed.

The evaluation of the penetration length shows a decrease in penetration length for the case that the remaining liquid fuel of the first injection is present at the moment when the second fuel injection starts. Since the influence of evaporation is decreased at a chamber temperature of 300 K compared to higher chamber temperatures, the penetration length of the second injection is always reduced at 300 K (see [Figure 13](#)). For increased ambient temperatures, e.g. 500 K or higher, a difference in penetration can only be observed for delays of 0.7 ms or less. The difference in penetration length at higher delays is relatively small when compared to the differences at 0.5 MPa 300 K. (see [Figure 14](#)).

Considering the difference in penetration length for single and double injection at 0.5 MPa 300K (see [Figure 13](#)), the deviation seems to be more dependent on chamber temperature than on chamber pressure. For lower chamber temperatures, evaporation slows down and more liquid fuel from the first injection is present. Therefore, the resistance affecting the penetration of the second injection event is increased. Prosperi [6] already mentions that the increase in ambient density amplifies the momentum exchange between the phases and consequently reduces the penetration length.

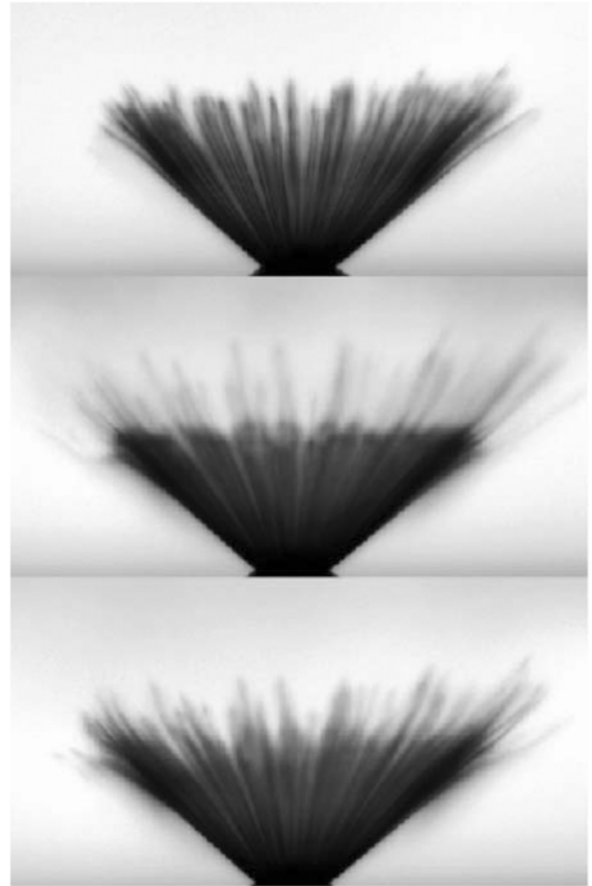


Figure 12. Pictures at 0.1 MPa chamber pressure and 300 K chamber temperature, single injection at 0.3 ms after energizing (top), double injection with delay 0.9 ms at 0.3 ms after start of second event (middle), double injection with delay 1.5 ms at 0.3 ms after start of second event (bottom)

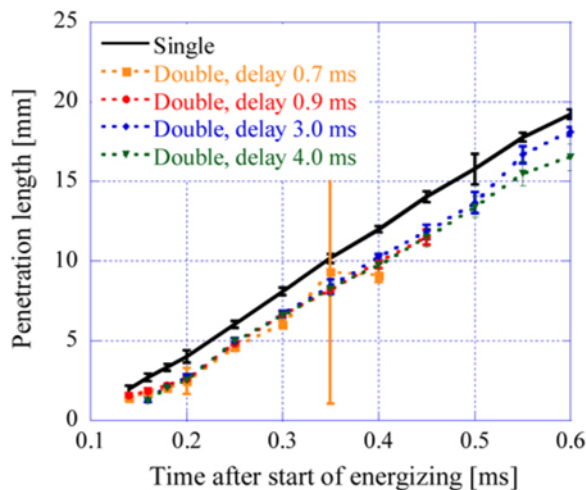


Figure 13. Penetration length for double injection at 0.5 MPa chamber pressure and 300 K chamber temperature

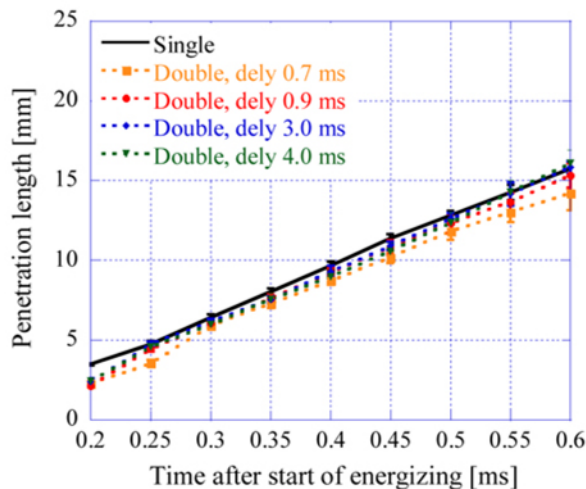


Figure 14. Penetration length for double injection at 1.0 MPa chamber pressure and 500 K chamber temperature

As mentioned previously, after closing the nozzle a toroidal vortex is formed and the evaporation becomes more important. The vortex is formed 0.6 ms after start of energizing the first or the second injection and increases. Eventually, the evaporation reduces the visibility of the vortex (see Figure 10). The vortex will be investigated exemplarily for 0.8 ms after start of energizing for all operating conditions and delays. Since the visual separation of both injections is not possible at this time, the toroidal vortex is evaluated without subtracting the image of the first injection from the image of the second injection. When using single injections at this point of time, the vortex is clearly visible and only slightly reduced by the evaporation. When comparing the images of the double injection events at 0.1 MPa in Figure 15, the original vortex of the single injection seems to move upward for the delays of 0.7 ms or 1.1 ms. Even for the highest delay investigated, which is 3.0 ms, the

vortex of the second injection is still different from the single injection. Increasing the ambient pressure to 0.3 MPa or 0.5 MPa the original vortex of the single injection can be weakly seen from a delay of 1.1 ms onwards. The vortex matches more and more the vortex of the single injection by increasing the delay between the two injections of the double injection, however, the exact same shape of the eddy cannot be recovered for double injection. Visually, the vortex is less dense for the double injection using a delay time of 4.0 ms. However, when increasing the ambient pressure up to 1.0 MPa (see Figure 15), the shape seems to change only slightly. The vortex can be observed for all delays. An increase in ambient pressure appears to maintain the vortex in shape and position by compression. In general the vortex consists of small droplets following the secondary air flow, that is induced by the spray. Increasing the ambient pressure the secondary air flow seems to be less influenced by the second injection and therefore the vortex is less affected. So the position and form of the vortex is mentioned to be stabilized by the increase in ambient pressure. Therefore, only the double injection for very small delay times shows different vortices if a high chamber pressure is used. It can be summarized that an increase in ambient pressure stabilizes the vortex. The flow field and the residual fuel of the first injection have less impact on vortex of the second injection. An increase in chamber temperature shows little effect on the disturbance of the vortex. Comparing the images for 0.5 MPa / 300K with 0.5 MPa / 500 K and a delay of 0.7 ms the vortices are different to the vortices of the single injection. Increasing the delay to 1.1 ms the vortices of single and double injection become similar to each other. Even the increase in temperature cannot avoid a variance in the spray shape between single and double injection, even though the increased evaporation reduces the interaction between the injections and make the vortices of single and double injections appear more similar.

So far, only the images of the backlight or scattering technique have been evaluated. Both types of images show only the outer shape of the spray. For further conclusions, also the images of the laser light sheet technique have to be analyzed, which show the inner structure of the spray cone. Caused by the dense spray during the injection, multiple scattering occurs using the laser light sheet measurement. Hence, the inner shape of the spray cone can only be investigated for the closed nozzle time interval when the spray is more dilute. The main purpose of the laser light sheet measurement is the investigation of the toroidal vortex. The laser light sheet images (see Figure 16), showing averaged images over 50 injection events, confirm the results of the scattering images, therefore only the operating conditions 0.5 MPa / 300 K and 1.0 MPa / 600 K are shown exemplarily. The boundaries are blurred due to the averaging over 50 injection events. Analogous to the images of the scattering technique at a delay of 1.1 ms, the laser light sheet images show a similar vortex for the single injection and the double