Velocity Measurement of High-Pressure Gasoline Direct Injections in the Primary Atomization Region on Flash Boiling Conditions

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Abstract
The primary atomization is the basis of the following spray and mixture formation. High optical density as well as high spray velocities up to 350 m/s (50 MPa GDI) in combination with spray structures in the µm-range are great challenges for measurement techniques. Therefore, the processes of the primary atomization are not fully understood yet, although these are very important for simulations of spray and mixture formation in modern combustion engines. For gasoline sprays, the velocity field close to the nozzle outlet is an important information for understanding and modelling the spray breakup process. Common measurement techniques like Phase-Doppler-Anemometry (PDA) are only able to determine reliable data starting from a distance of 30 mm to the nozzle and low-pressure conditions. More specialized measurement techniques like x-ray Phase Contrast Velocimetry (PCV) used at the Argonne National Laboratory deliver velocities very close to the nozzle outlet, but are highly complex and allow only a very limited measurement time. For these reasons, the Structural Image Velocimetry (SIV) was developed to get a technique able to measure velocity fields in the first millimetres after the nozzle outlet for high-pressure fuel injections with an easier applicability. The SIV combines basic ideas of Laser Correlation Velocimetry (LCV) with the post-processing of Particle Image Velocimetry (PIV) to measure 2D velocity fields. Using a homogenous background illumination, structures inside the spray are obtained by a lens system with a very small focal depth and a high resolution (~ 1…5 µm/px). Based on cross correlation, the structures are tracked and evaluated to determine a 2D velocity field. The SIV results have been validated by comparing with x-ray PCV measurements on a same injector system in a previous study. In this study, spray velocity measurements of the first millimetres of a modern gasoline injector are presented. The velocity fields on different operating conditions also including flash boiling (0.03 MPa gas pressure / 363 K fuel temperature) and high injection pressures up to 50 MPa are investigated.

Keywords
Primary Breakup; Primary Atomization; Spray Velocity; SIV; Flash Boiling

Introduction

High pressure injection systems are commonly used in modern gasoline engines. The design parameters of the systems, especially about injectors, are one of the most important aspects for producing the next clean engines because it affects the spray, fuel mixture formation, and combustion. In the first millimetres from the injector nozzle, the injected liquid fuel jet dramatically break up into ligaments and droplets (Primary breakup), then these ligaments and droplets break up into many small droplets (Secondary breakup). Although this spray breakup process in the near nozzle region plays a major role on the spray formation, only limited numbers of measurement results have been reported yet because of the measurement difficulty. Due to the very high optical density and simultaneously structures in the µm-range with high velocities up to 350 m/s, a detailed measurement of this region is very challenging. Those detailed measurements are needed both for the development of physical models to understand the processes as well as to develop and validate numerical simulations. For this purpose, several measurement techniques are developed and also unique results are reported. A review of the measurement techniques used for obtaining information in this spray region from 2000 up to 2013 was done by Linne [1].

A very important information for gasoline sprays is the velocity field close to the nozzle outlet [2]. Common measurement techniques like Phase-Doppler-Anemometry (PDA) are only able to determine reliable data starting from a distance of 30 mm to the nozzle and low-pressure conditions [3]. More specialized measurement techniques like x-ray Phase Contrast Velocimetry (PCV) used at the Argonne National Laboratory deliver velocities very close to the nozzle outlet, but are highly complex and allow only a very limited measurement time [1,2]. Because of this background, a new measurement technique which is capable to measure velocity fields in the first millimetres after the nozzle outlet for high-pressure fuel injections with an easier applicability has been required. Structural Image Velocimetry (SIV) is developed as such a technique. The SIV combines basic ideas of Laser Correlation Velocimetry (LCV) with the post-processing of Particle Image Velocimetry (PIV) to measure 2D velocity fields. Using a homogenous background illumination, structures inside the spray are obtained by a lens system with a very small focal depth and a high resolution (~ 1…5 µm/px). Based on a cross correlation method, the structures are tracked and evaluated to determine a 2D velocity field. Comparisons with x-ray PCV measurements were used to validate the SIV results [4]. A similar approach, the so-called Shadow Particle Image Velocimetry (SPIV) was used by Weber and Leick to measure velocity fields of gasoline sprays [5].

In this study, spray velocity measurements in the first millimetres of a modern gasoline injector are performed. Here the gasoline fuel dramatically breaks up to small structures, which are the combination of ligaments, films and droplets, so that the name "Structural Image Velocimetry" seems to describe well what the measurement technique measures. The fuel temperature, gas pressure, and injection pressure are elevated to investigate the effect of these parameters on the spray formation. Another important aspect is the formation on flash boiling condition. To achieve the flash boiling condition, the spray chamber was evacuated to 0.03 MPa and the fuel temperature is controlled to keep 363 K. The results are compared and discussed with the results on other conditions to clarify the effect of environmental and injection conditions.

Material and methods

All measurements with the SIV were conducted at our high-pressure high-temperature (HPHT) vessel. This vessel was designed in the past primary as a vessel for diesel spray investigations and uses the method of premix combustion of hydrogen to reach diesel engine like conditions. For gasoline investigations, the requirements concerning the gas pressure and temperature do not need premix combustion, but require a possibility to reach pressures below atmospheric. For this, a vacuum pump is used at the chamber. In all, the HPHT vessel is able to ensure all operating conditions. For the spray investigations, a solenoid gasoline injector from CPT Group GmbH (previously Continental Powertrain) is used because of its capability to reach 50 MPa injection pressure. This serial injector is only modified with a reduced amount of nozzle holes of three to be able to investigate one independent spray cone in side view. All measurements were done with Ethanol and during the stationary phase of the injection to see the dominant breakup mechanism. Starting from a reference point (OP1), the fuel temperature (OP2, OP3), the gas pressure (OP4, OP5) and the fuel pressure (OP6, OP7) are variated. Finally, flash boiling conditions (OP8) were investigated. In all, only one parameter is changed at a time to see the influence on the breakup and the velocity. Table 1 shows all conditions for the different operating points.

Table 1. Operating points for variation of fuel temperature, gas pressure, fuel pressure, and flash boiling condition

Operating Point	Fuel Pressure	Fuel Temperature	Gas Pressure	Gas Temperature
OP1	35 MPa	298 K	0.1 MPa	298 K
OP2	35 MPa	263 K	0.1 MPa	298 K
OP3	35 MPa	363 K	0.1 MPa	298 K
OP4	35 MPa	298 K	0.03 MPa	298 K
OP5	35 MPa	298 K	0.3 MPa	298 K
OP6	24 MPa	298 K	0.1 MPa	298 K
OP7	50 MPa	298 K	0.1 MPa	298 K
OP8	35 MPa	363 K	0.03 MPa	298 K

The working principle of the Structural Image Velocimetry is illustrated in Figure 1. It combines two established measurement techniques, the LCV and PIV. LCV was developed by [6] in such a way that two focal points are illuminated in the middle of the spray with a defined small distance Δx in the mean flow direction. With suitable optics, the Mie scattering signal is observed with two photodetectors aside of the spray, where the time-dependent signals are digitized with a high data rate in the multi-kHz range. Two detected time series are compared via cross-correlation analysis delivering the correlation time shift Δt. In combination with the known distance of the focal points, the velocity of the spray structures can be determined. The measurement technique is found to be applicable even in the very near field of the spray [7–9]. The most probable signal is coming from the focal points, while the multiple scattering from structures or droplets before or behind these points has a certain background noise influence, depending on the depth of field of the detection optics.

The SIV illuminates the spray using a diffuse backlight illumination. The spray is captured by a camera equipped with a lens system. The backlight should produce a homogenous illumination to ensure a good visualization also of very small droplets and structures. A high magnification of the lens system is used to detect the first millimetres of the spray. Due to the very high optical density of sprays in this region, a very small depth of field is used to slice the spray at the focal plane to be able to detect also structures at this position and like LCV reduce the signal from droplets before or behind this focal plane. The SIV is based on the idea from PIV that also spatial cross-correlations between two consecutive images can give the information on the velocity, now even in the two-dimensional measurement plane. While for the PIV technique this plane is defined by a laser light sheet with double exposure [10] the application of such light sheets in the very near field of a spray is seen to be too much disturbed by the multiple scattering of the dense spray [11,12]. Instead, the idea from the LCV technique is adopted that the spray volume is illuminated, but that the observation lens system, in this case a long distance microscope, determines the observation plane due to its very small depth of field to slice the spray in a certain plane (Figure 1). Therefore, the influence of the other spray areas out-of-focus is rather small and measurements in the spray centre are possible.

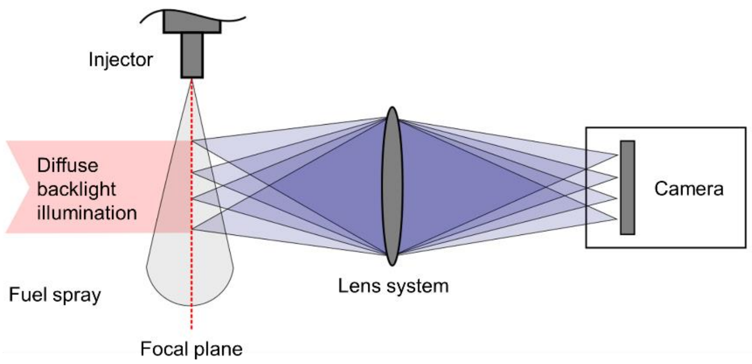

Figure 1. Working principle of the Structural Image Velocimetry [13].

For the cross-correlation evaluation of the SIV technique, it is not required that droplets have formed. Instead, any sort of moving structures of the spray can lead to a correlation, from which the velocity of these structures can be derived, as long as the live time of these structures is in the order or larger than the measurement time between two consecutive images. Both requirements are similarly necessary for the LCV and the SIV method. Depending on the local optical density and the two-phase structures of the spray, it can be expected that already quite near to the injector outlet a measurement signal can be obtained. Especially for gasoline sprays where the primary breakup already starts inside the nozzle hole due to strong cavitation. One aim of this research work was to determine the smallest distance to the injector where the SIV technique is applicable and if a wide range of operating conditions can be measured.

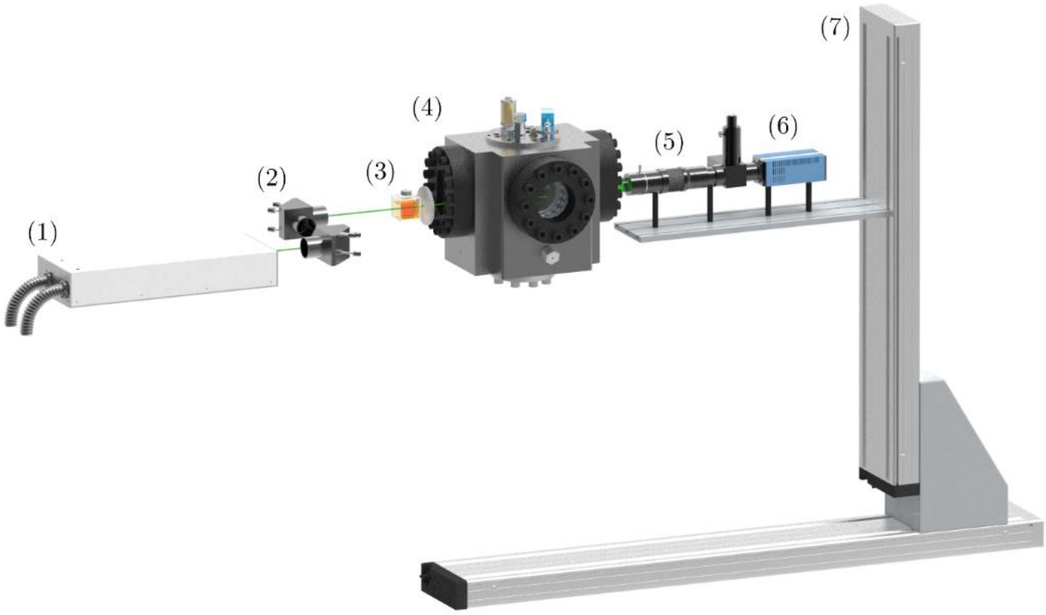

Figure 2. Experimental setup of the Structural Image Velocimetry at the high-pressure high-temperature vessel.

The working principle shown in Figure 1 is implemented at the HPHT vessel using the following components and illustrated in Figure 2. A double pulse laser (1) with pulse durations of 8 ns to mostly reduce motion blur is used as a backlight illumination whose laser beam is adjusted via deflection mirror (2). Due to the coherence of the laser light, the produced backlight illumination would consist of many speckles and therefore be not very homogenous. To ensure a more homogenous backlight illumination, a combination of a fluorescence fluid and a diffuser screen (3) reduce those speckles. This diffuse backlight illumination is used for visualizing of the spray inside the HPHT vessel (4), which is then captured by a double shutter camera (6) with only 0.5 µs between the frames. To achieve very high magnifications and simultaneously very small depth of field, a long distance microscope (5) is applied to the camera. The very small depth of field requires a precise adjustment of the camera to focus on the spray centre plane (equivalent to *Focal plane* in Figure 1). Therefore, a high precision traverse (7) is used with a repetition accuracy of 20 µm. The detailed parameters of the experimental setup are given in Table 2.

Table 2. Specification of the experimental setup.

Double pulse Nd:YAG-Laser		**Double shutter camera**		**Long distance microscope**	
Wave length	532 nm	Image resolution	1600 x 1200 px	Resolution	3.386 µm/px
Pulse duration	8 ns	Pixel size	7.4 x 7.4 µm^2	Depth of field	100 µm
Pulse energy	159 mJ	Δ*t* of images	0.5 µs	Field of view	5.4 x 4.1 mm^2

Measurements with the experimental setup presented in Figure 2 deliver raw images shown in Figure 3. Those raw images show the spray during the stationary phase of the injection 1000 µs after start of energising (ASOE). The nozzle outlet is located at the coordinates (0/0). On the left side, a raw image is shown. Starting from approximately 2 mm, structures became visible even in the centre of the spray getting clearer with an increasing distance to the nozzle outlet. Those structures are clearly visible and move a certain distance Δ*x* during the time between the images Δ*t* giving the velocity *v* of this structure. Looking at the raw image and the noticeable structures, a reliable velocity field can be expected starting at approximately 2 mm from the nozzle exit. Adjusting the brightness and contrast of these raw images, structures in the centre on the spray even starting at 1 mm can be seen.

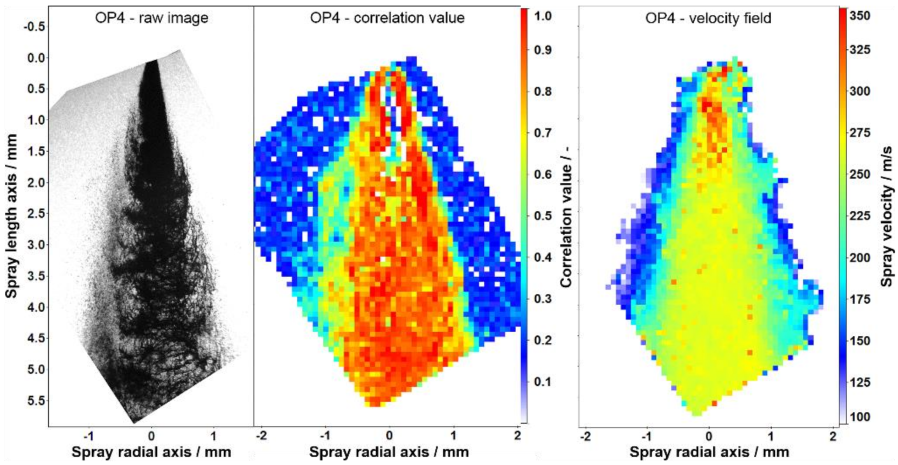

Figure 3. Raw image (left), correlation values (middle) and velocity field (right) from SIV measurements of OP4.

During the post processing routine, the cross correlation between two consecutive images is calculated for all 30 injections per operating point. Evaluation of the raw image on the left side in Figure 3 leads to correlation values illustrated in the middle of the figure. The correlation values can be divided into three areas of the spray. The spray centre generates high correlation values around 0.9 starting at a distance of approximately 2 mm from the nozzle outlet. The area direct at the nozzle outlet has also high correlation values at the edges of the spray, but not in the centre, where the algorithm is not able to track structures reliable. The edges of the spray were mostly small ligaments and droplets are present, has correlation values around 0.5 probable due to the noise background. In all, the algorithm detects most parts of the spray with high correlation values. Therefore it can be assumed, that the quality of the raw images is well enough for structure tracking even in the centre of the spray. The calculated high-resolution velocity field of the spray is shown on the right side. For a better visualisation of the velocities, the vector direction, which is mostly going downstream the spray, is left out and the vector length is given by a colour-map. Due to the very dense spray directly at the nozzle outlet, the velocities in this area are not trustworthy. Starting at approximately 2 mm from the nozzle, the velocity field develops a typical radial distribution with high centre velocities and velocities at the edges of the spray of about 50 % of those. A relation between the correlation value and the velocity was also tested, but no signification dependency could be evaluated. Similar algorithms for the evaluation of spray structure images are described in [5,14].

Results and discussion

Measurement results during the stationary phase of the injection (1000 µs ASOE) from the Structural Image Velocimetry are presented in the following section. Here, the average velocity field of 30 injections per operating point is shown for all different conditions. Changing one parameter at a time, the influence on the spray velocity should be visible. Furthermore, the ability of the SIV to investigate gasoline sprays under a wide range of experimental conditions is tested.

Fields of velocity and standard deviation on the velocity

Before starting the discussion of the different operating conditions, fields of velocity measured by SIV and the standard deviation of the velocity are shown in Figure 4. The figure on left side shows the velocity fields indicated by a colour-map. The vertical axis indicates the distance from the injector nozzle and the horizontal axis indicates the distance from the spray centre. The results show relatively high velocities (red) near the nozzle around the spray centre. Also some dots show the high velocity around 5 to 5.5 mm downstream from the nozzle. There is an edge of measured fields, thus it might be caused by a relatively low SNR because the traced structures are reached to the border of measurement fields. The low velocities (blue) appear on the edges of the spray. The velocity distribution in the radial direction of the spray shows the high value in the centre and the low value at the periphery, which fits quite good with the common understanding of spray velocities.
The standard deviation on the velocity shows high value (red) around the spray centre near the nozzle. It might be caused by the optical density of the fields near the nozzle, which is affected by relatively high frequent breakup. Relatively high (green) region is apparent near the periphery entire the spray. It might be caused by the temporal spray structure fluctuations and shot-to-shot variations of the spray. The region around the spray centre in 3 to 5 mm from the nozzle shows relatively low (blue) and it means that there are relatively steady during the injection. Therefore the distance 4 mm from the nozzle is chosen as a plane for further qualitative comparison in steady states of the velocity distribution in radial direction of the spray.

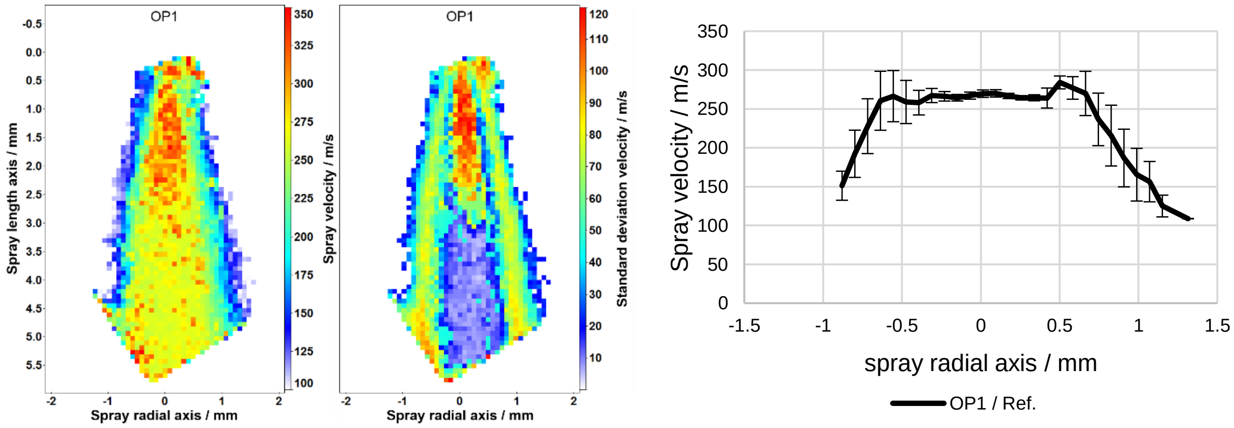

Figure 4. Velocity field (left), standard deviation of velocity (middle) and velocity profile in 4 mm distance to the nozzle outlet (right) for OP1 (Ref.).

Effect of fuel temperature on the velocity

The results on OP2 (263 K) and OP3 (363K) are shown in Figure 5. The left side is velocity fields and the right side is the velocity distribution in radial direction of the spray with error bars, which indicates standard deviations. As shown in the velocity fields figure, the outer shape of the spray is almost same but the velocity on the high temperature condition is higher than that at the low temperature condition. It is caused by the decreased fuel viscosity by increasing the temperature of the fuel. The radial distributions show the similar velocity profiles but slightly higher almost entire the spray in case of OP3.

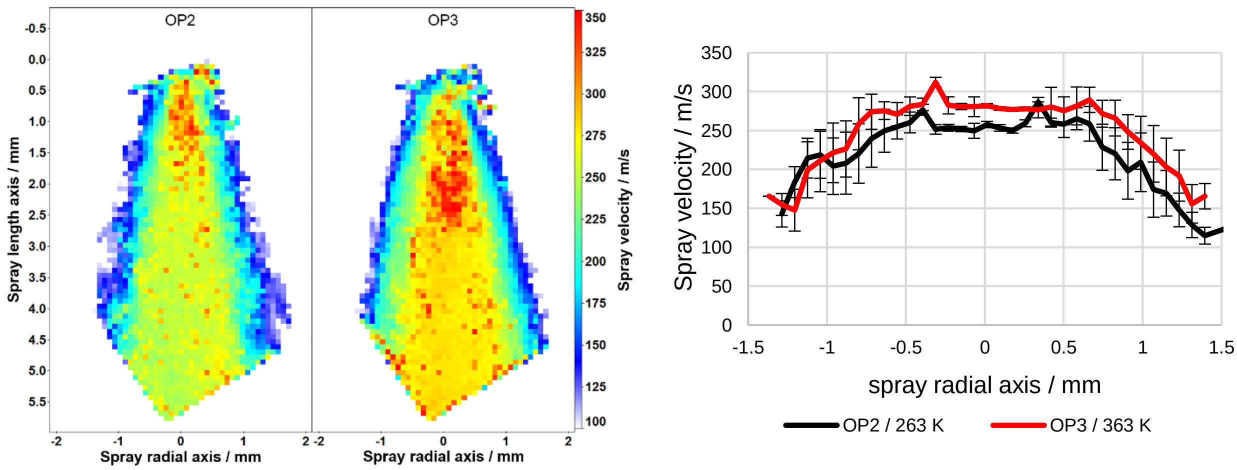

Figure 5. Velocity field (left) and velocity profile in 4 mm distance to the nozzle outlet (right) for OP2 (263 K) and OP3 (363 K).

Effect of back pressure on the velocity

The results on OP4 (0.03 MPa) and OP5 (3 MPa) are shown in Figure 6. As shown in the velocity fields figure (left), the outer shape of the spray on the low back pressure condition is wider than that at the high backpressure condition. Also, the velocity around spray centre on the high back pressure condition keeps high velocity towards the downstream. It is considered that the high backpressure makes poor air entrainment near the nozzle and it lead the small spray angle and keeping the velocity around the spray centre. According to the radial distribution of the velocity, the spray width of OP4 is 1.5 times larger than that of OP5.

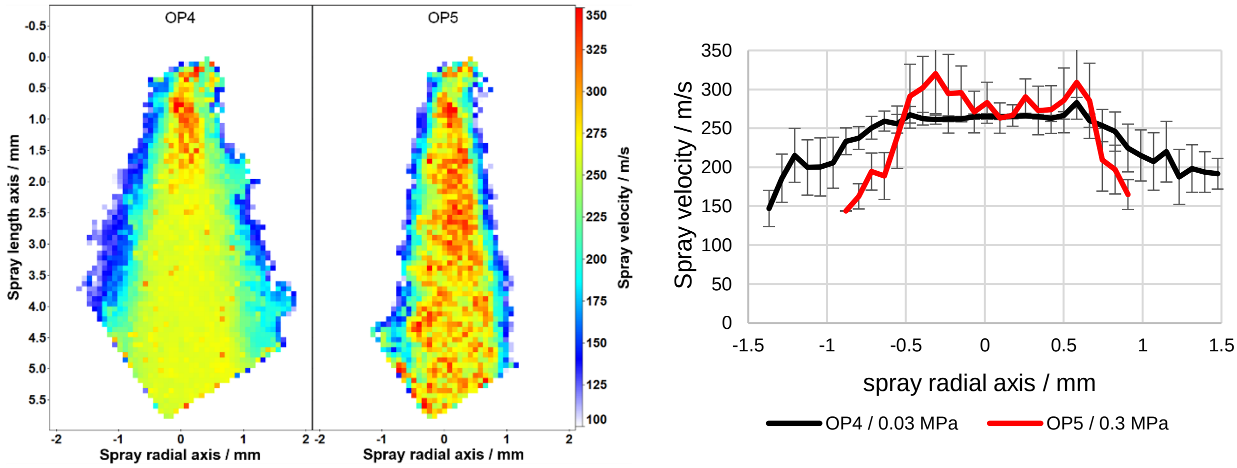

Figure 6. Velocity field (left) and velocity profile in 4 mm distance to the nozzle outlet (right) for OP4 (0.03 MPa) and OP5 (0.3 MPa).

Effect of injection pressure on the velocity

The results on OP6 (24 MPa) and OP7 (50 MPa) are shown in Figure 7. As shown in the velocity fields figure, the outer shape of the spray is not changed so much but the velocity on the high injection pressure condition is higher than that at the low injection pressure condition. Similar tendency is also shown in the comparison of low and high fuel temperatures. The almost constant increasing of the velocity is apparent on the entire radial direction of the spray in the fuel temperature comparison. On the other hand, the increasing of the velocity is apparent especially around the spray centre in the injection pressure comparison.

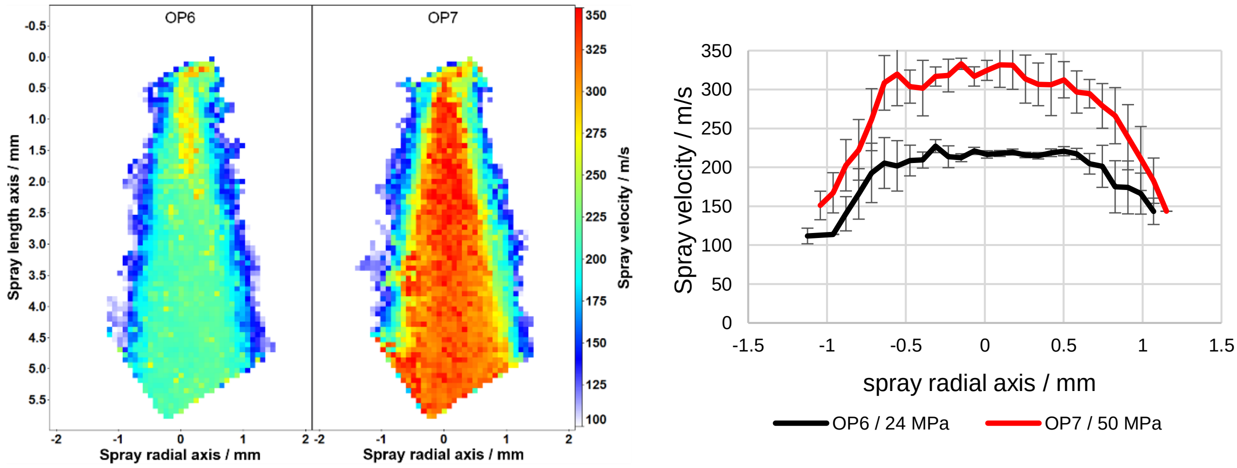

Figure 7. Velocity field (left) and velocity profile in 4 mm distance to the nozzle outlet (right) for OP6 (24 MPa) and OP7 (50 MPa)

Effect of flash boiling on the velocity

When the flash boiling occurs, fuel bubbles appear in the injector nozzle. It will grow and collapse near the nozzle region, which breaks up the fuel drastically. It makes fine and wide angle spray. To be clarified the effect of the different breakup phenomenon, the spray chamber was evacuated to 0.03 MPa and the fuel temperature is controlled to keep 363 K to achieve the flash boiling condition.

The raw image and velocity field on flash boiling condition (OP8) are shown in Figure 8 (left). As shown in the figure, the spray covers almost the entire measurement field. The raw image which taken at OP4 (same back pressure but low fuel temperature) is shown in Figure 3. Comparing these raw images, the spray outer shape on OP8 is drastically wide and the structure at the outer edge of the spray is relatively small and smooth.
From the parametrical comparisons, the fuel temperature effects are not so much appeared on the spray outer shape but are slightly appeared on the velocity. And the back pressure effects appear on the spray width. Considering the combination of these effects, the assumed results of OP8 will be similar width of that on OP4 but the velocity is slightly higher. The actual results of OP8 shows much wider spray direct after leaving the nozzle already. The difference between the actual and assumed results is simply caused by a flash boiling occurs or not.
In Figure 8 (right), the velocity fields of OP3, OP4 (without flash boiling) and OP8 (flash boiling) are compared on 3 mm from the nozzle to be clarified the difference on the velocity, because the spray of OP8 is already reached to outside of the measurement area at 4 mm from the nozzle. The results of OP3 (Fuel temperature 363 K) and OP4 (Back pressure 0.03 MPa) are already mentioned in Figure 5 and 6. The velocity distribution on OP8 almost shows higher values than other OPs entire the radial direction of the spray. The velocity distributions on all OPs show almost flat in the range of -0.5 to 0.5 mm in radial direction. Outside of the range, the velocities on each condition are decreased towards the spray periphery. The velocity on OP8 is decreased much gradually compared to that at the other OPs. The velocity at the periphery on OP8 is 200 m/s and that on the others are around 150 m/s. It is considered that the fine and wider spray accelerates a momentum exchange from the spray to the surrounding air and therefore the velocity distribution on OP8 shows flat and high velocity entire the spray. Also, it can be concluded that the SIV is possible to recognize the difference on the spray character caused by a breakup like flash boiling phenomena near the nozzle region.

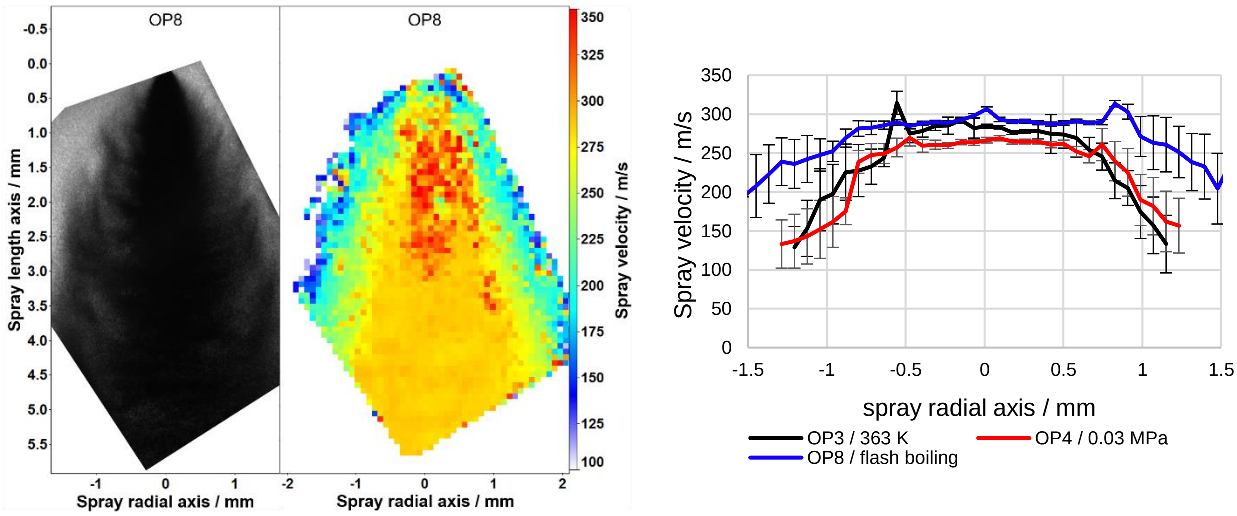

Figure 8. Raw image and velocity field (left) and velocity profile in 3 mm distance to the nozzle outlet (right) for OP3 (363 K), OP4 (0.03 MPa) and OP8 (flash boiling).

Conclusions

Spray velocity measurements in the first millimetres of a modern gasoline injector are performed by Structural Image Velocimetry. The fuel temperature, gas pressure, and injection pressure are elevated to investigate the effect of these parameters on the spray formation. Also other important aspect is the investigation of the formation on flash boiling condition. To achieve the flash boiling condition, the spray chamber was evacuated to 0.03 MPa and the fuel temperature is controlled to keep 363 K. The results are compared and discussed with the results on other conditions to clarify the effect of environmental and injection conditions.
The reference operating point (under atmospheric back pressure and ordinary temperature) results of the velocity distribution in the radial direction of the spray shows high values in the centre and low values at the periphery, which fits quite good with the common understanding of spray velocities. The standard deviation on the velocity shows high value around the spray centre near the nozzle. It might be caused by the optical density of the fields near the nozzle, which is affected by relatively high frequent breakup. Also relatively high standard deviations are appeared near the periphery entire the spray. It might be caused by the temporal spray structure fluctuations and shot-to-shot variations of the spray. Therefore, it can be mentioned that the SIV is able to obtain the velocity field data in first millimetres from a gasoline injector under atmospheric condition, and its deviation distribution is reasonable assuming from the phenomena inside spray.
From the parametrical comparisons, the fuel temperature effects are not so much appeared on the spray outer shape but almost constant small increasing of the velocity with increasing the temperature appears entire the radial direction of the spray. The back pressure affects the spray width. Higher back pressure leads to slightly wider spray.

The increasing of the velocity by increasing the injection pressure appears especially around the spray centre. The condition of the flash boiling occurring shows remarkable difference from the other conditions. The spray outer shape is drastically wide and the structure at the outer edge of the spray is relatively small and smooth. The velocity distribution on flash boiling condition shows flat and high velocity entire the spray. It is considered that it is a result of the fine and wider spray accelerating a momentum exchange from the spray to the surrounding air. Over all from the parametrical comparison, it can be concluded that the SIV is able to recognize the different spray characteristics in terms of velocity fields of gasoline sprays in the first millimetres after the nozzle outlet caused by different fuel temperatures, back pressures, and injection pressure.

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Nomenclature

Δt	Time between two consecutive images
v	Spray velocity
Δx	Structure movement

ASOE	After start of energisation	PCV	Phase Contrast Velocimetry
GDI	Gasoline direct injection	PDA	Phase Doppler Anemometry
HPHT	High-pressure high-temperature	PIV	Particle Image Velocimetry
LCV	Laser Correlation Velocimetry	SIV	Structural Image Velocimetry

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