Two-Phase PIV: Fuel-Spray Interaction with Surrounding Air

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Abstract. The demand for improvement of combustion-engine processes leads to a great need for detailed experimental information about the complicated processes of injection, breakup and propagation of the fuel jet and the vaporization of the fuel.

Thus, in the presented work it was the aim to visualize the air flow that is induced by the injected fuel jet and also to explore the air entrainment into the fuel spray. This was done using two-phase PIV (particle image velocimetry).

The fuel jet was illuminated with a Nd:YAG PIV-laser and PIV analysis was done by simply measuring the elastically scattered light of the fuel droplets. For the investigation of the surrounding air propylene-carbonate doped with DCM-dye was dispersed and the droplets were added to the continuous gas flow upstream of the chamber. Scattered and fluorescence signals, respectively, were detected perpendicular to the laser sheet with a CCD camera. To detect the gas flow, the scattered light from the liquid fuel was suppressed by an OG 590 longpass filter glass that transmits the fluorescence signal of the DCM-dye.

It was possible to measure both the fuel jet and the gas flow in the presence of the fuel spray and a clear separation of the two phases could be achieved.

In both (fuel and air) vector pictures corresponding vortices could be identified near the air/fuel boundary layer. Maximum velocities in the jet are depending on the operation conditions up to $150\,\mathrm{m\,s^{-1}}$ and the gas flow has typically a velocity of 1 to $10\,\mathrm{m\,s^{-1}}$.

In the region next to the injector the air was pressed away during the injection. After the end of the injection a strong fast air entrainment flow into this region can be observed that compensates the pressure difference.

1 Introduction

The demand of people for flexible mobility is further increasing and thus the car remains an important factor to meet this demand. In spite of extensive research for alternative engines, the combustion engine will stay the most important solution for the next few decades. At the same time one is facing declining resources and increasing environmental stresses. This means that the requirement to improve combustion-engine processes to reduce both fuel consumption and emissions is greater than ever. This led, amongst others, to the development of modern direct-injection concepts for spark-ignited engines for which it is important to ensure the provision of a burnable air–fuel

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mixture at the spark plug at the moment of ignition [1]. Further improvement necessitates comprehensive modeling of the fuel-mixture generation and there is a great need for detailed experimental information about the complicated processes of injection, breakup and propagation of the fuel jet and the vaporization of the fuel as input data for calculations and computational fluid dynamics (CFD) [2].

In the presented work it was the aim to analyze the air–fuel interaction. The injected fuel jet induces an air flow that was to be visualized and also the air entrainment into the fuel spray was to be explored. Furthermore, the motion of the fuel droplets and the development of vortices are of great interest regarding fuel vaporization and provision of a burnable mixture. To gather information about these aspects it is necessary to measure the flow of both phases, liquid fuel and gaseous air, for which the application of two-phase PIV is ideal [3]. Similar investigations were made by *Kubach* et al. [4] who combined PIV with shadowgraphy. They did not, however, examine the interaction between air and fuel.

2 Experimental

The investigations were performed in an optically accessible pressure chamber since the experimental effort is reduced in comparison with engine measurements and allows an easy variation of operating conditions. The relevant phenomena of the mixture generation in this part of the combustion process are only weakly affected by the geometry of the engine and can be observed in detail in a chamber.

Thermodynamic conditions similar to those in the engine can be realized and the optical accessibility is very good. Special air flows, e.g., a tumble changing with the crank angle that can be found in the engine, however, cannot be simulated in the used chamber. Nevertheless, for general investigations on mixture formation this does not represent a major drawback.

The injector was placed in the top of the chamber and the direction of the fuel spray is downwards. There is an air flow continuously streaming through the chamber to scavenge the remains of the injections. The resulting maximum frequency of alternating injections is about 3 Hz. The air can be heated to 400 °C and the pressure in the chamber can be varied from 0.2 to 42 bar.

The light of a frequency-doubled Nd:YAG PIV laser was formed into a lightsheet with a height of approximately 100 mm and a pair of pictures for PIV analysis of the fuel jet was taken by simply measuring the elastically scattered light of the fuel droplets. There are enough separated droplets and this approach works for most of the investigated operating points after 50 to 100 µs after the first fuel leaves the injector because of the high injection pressure results in a fast spray breakup.

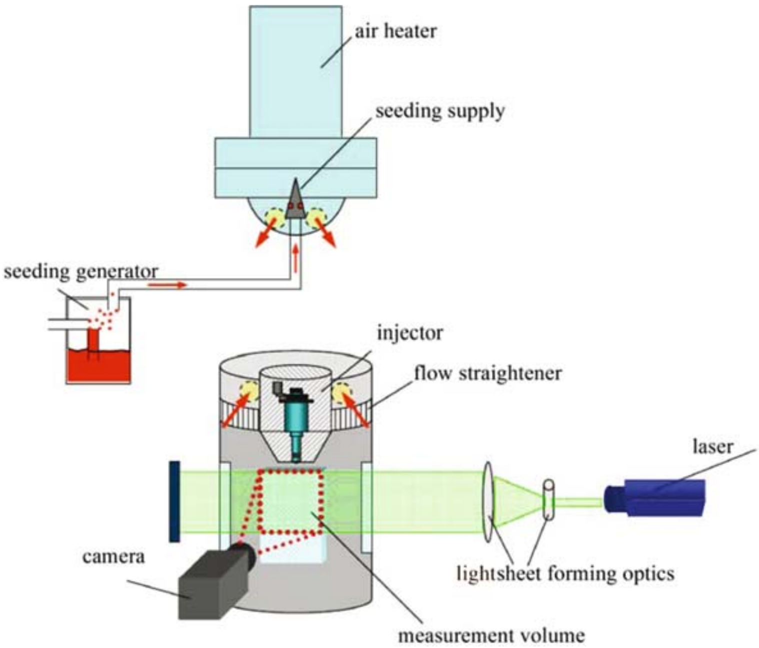

Fig. 1. Experimental setup: top of the chamber with seeding supply and optical setup

For the investigation of the surrounding air propylene carbonate doped with DCM-dye was dispersed by a commercial seeding device and the droplets were added to the continuous gas flow upstream of the chamber. The dye can be excited at 532 nm and emits in the region of 620 to 690 nm with a maximum emission around 660 nm.

The seeder was driven with pressurized air (less than 0.6 MPa) and worked without problems up to a counterpressure of 0.4 MPa.

Scattered and fluorescence signals, respectively, were detected perpendicular to the laser sheet with a double-shutter CCD camera. To detect the gas flow the scattered light from the liquid fuel was suppressed by an OG 590 longpass filter glass that transmits the fluorescence signal of the DCM-dye.

The PIV evaluation was done with LaVision Davis 7.1. In the preprocessing a constant background was subtracted. A crosscorrelation analysis was performed. The size of the interrogation areas was varied in a multipass approach starting with 128×128 decreasing to 32×32 pixel or 16×16 pixel for the fuel jet with an overlap of 25 or 50 % or to 64×64 pixel and 32×32 pixel for the gas flow.

In the postprocessing only a median filter was used to suppress noise vectors. The optimal setting of the calculation parameters had to be adjusted depending on the individual operating conditions.

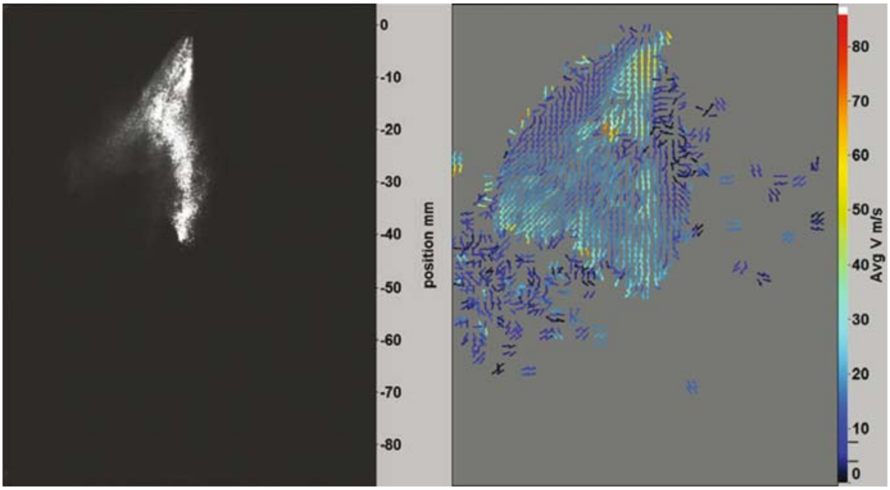

Fig. 2. Raw scattering signal of the fuel spray and corresponding vector picture

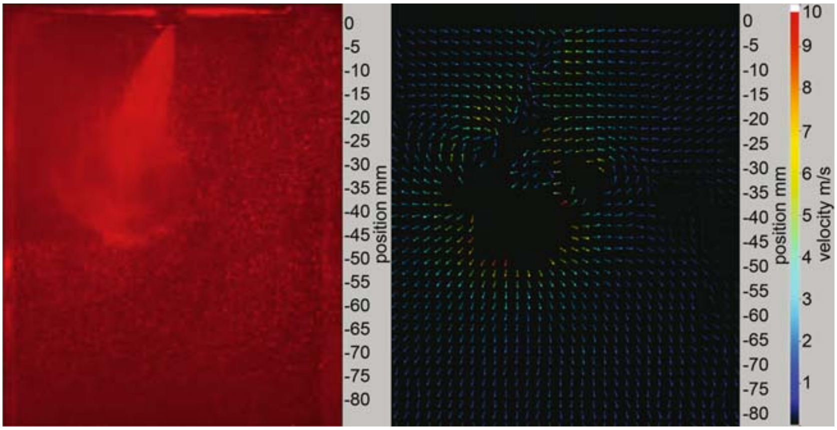

Fig. 3. Fluorescence signal of dye in the gas seeding and corresponding vector picture

The repetition rate of the PIV system is about a few Hz. Thus, only one pair of pictures can be detected for one injection and the temporal evolution of the investigated flows can only be observed in successive injections.

In Fig. 2 a typical detected scattering signal is shown. The laser lightsheet enters the chamber from the right side. This causes higher scattering intensity in the raw pictures on this side of the spray due to laser absorption when traveling through the dense spray. This did not affect the quality of the PIV analysis.

A fluorescence picture is depicted in Fig. 3. A dense distribution of seeding particles can be seen. This results in the fact that the outline of the fuel jet is clearly visible. This strong signal is not elastically scattered light that passes the longpass filter glass but the intense scattering in the fuel spray induces fluorescence between the spray and the camera outside the laser lightsheet. Furthermore, shadowing effects of the spray can be observed on the left side. The surrounding gas flow can be reconstructed by the PIV analysis. No vectors are found in the dense spray.

The temporal evolution of the flow was evaluated by shifting the recording time by 50 µs from 0.3 to 2 ms after the start trigger of the injection. The injection ends, depending on the operating conditions, around 1.3 ms.

The time delay between the two PIV pictures was chosen individually for each operating point, depending on the conditions, especially the average flow velocity. For the visualization of the fuel jet the optimal time delay was between 1.5 and 8 µs. For the analysis of the slower gas flow, delays between 30 and 100 µs were chosen. One possible option would be the use of an image splitter with the longpass glass filter in front of one side of the picture to detect simultaneously both flows within one pair of pictures. Another approach could be the use of one color camera, which was suggested by *Towers* et al. [5], but the limited dynamic range of the camera causes problems in this case. Besides these considerations, the difference in optimal delay time made the simultaneous detection unfortunately impossible.

Thus, a sequential method was employed, i.e., first the gas flow was detected with a filter in front of the camera and an optimized time delay, and in a second experimental set the fuel jet was observed with the same operating conditions of the pressure chamber. The reproducibility of the injection is quite good; nevertheless, there are cyclic fluctuations when using high-pressure injectors, making a statistical analysis of the measured data necessary. For each point, 20 vector pictures were generated and averaged for the fuel and the air flow, respectively.

3 Results

It was possible to measure both the fuel jet and the gas flow in the presence of the fuel spray and a clear separation of the two phases could be achieved. In both (fuel and air) vector pictures corresponding to vortices could be identified near the air/fuel boundary layer as shown as an example in Fig. 3. These are essential for the preparation of a burnable mixture since fuel droplets leave the spray and they slow down. Thus, more time for vaporization is available. Simultaneously, air enters the fuel jet.

Maximum velocities in the jet depend on the operation conditions up to 150 $\mathrm{m\,s^{-1}}$ and the gas flow has typically a velocity of 1 to 4 $\mathrm{m\,s^{-1}}$. In the region next to the injector the air was pressed away during the injection. After the end of the injection a strong fast air entrainment flow into this

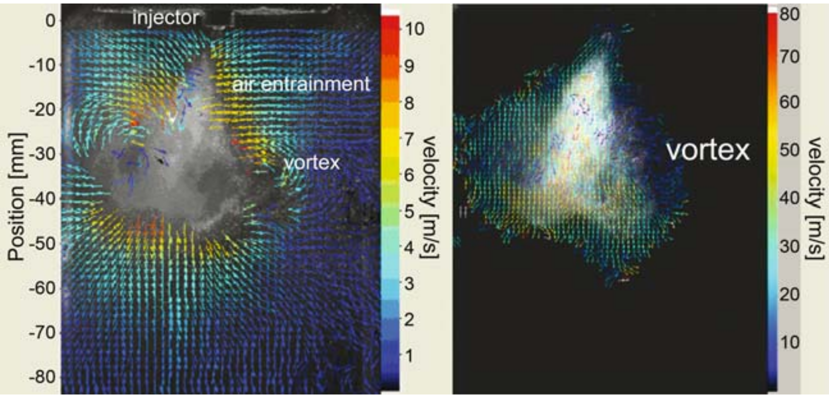

Fig. 4. Vector field of gas flow (*left*) with induced swirls and strong air entrainment (the fuel spray is displayed in the *background*) and corresponding flow field of fuel droplets (*right*)

region can be observed that compensates the pressure difference. The gas is accelerated up to $15\,\mathrm{m\,s^{-1}}$.

In Fig. 5 the influence of the chamber pressure on the fuel spray is shown. The penetration length decreases with increasing counterpressure. Additionally, the fuel jet is slowed down and becomes more compact. In the bottom part of the picture one can see that the velocity of the induced air flow corresponds to the velocity of the fuel droplets in the spray: where the fuel enters the chamber with high speed the air is stronger accelerated. The intensity of the air entrainment decreases with increasing chamber pressure. Also, the vortex in the region of the air/fuel boundary layer is less pronounced, which may lead to a worse mixture preparation. The development of the vortices in the fuel jet is similar to the results of calculations, e.g., from *Gavaises* [6].

The complete development of the air flow is shown in Fig. 6. In the first picture the undisturbed continuous scavenging gas flow is observable. Then the fuel jet begins to penetrate the chamber and the air is pushed away. The air is accelerated up to 7 m/s. Later, the strong air-entrainment flow into this region with reduced pressure starts.

Furthermore, it was investigated whether the scavenging gas flow has an influence on the jet behavior and the fuel–air mixture generation.

A variation of the gas mass flow shows higher flow velocities in the continuous gas flow but does not affect the fuel jet flow, nor the induced gas flow, as shown in Fig. 7.

The mass flow is increased by a factor of 4 and, as one would expect, the maximum velocities of the gas flow before the start of injection increase from 0.25 to $1\,\mathrm{m\,s^{-1}}$, i.e., by almost the same factor.

The pictures of the fuel-droplet motion as well as the induced gas flow, however, are quite similar. In the bottom row differences appear only in the

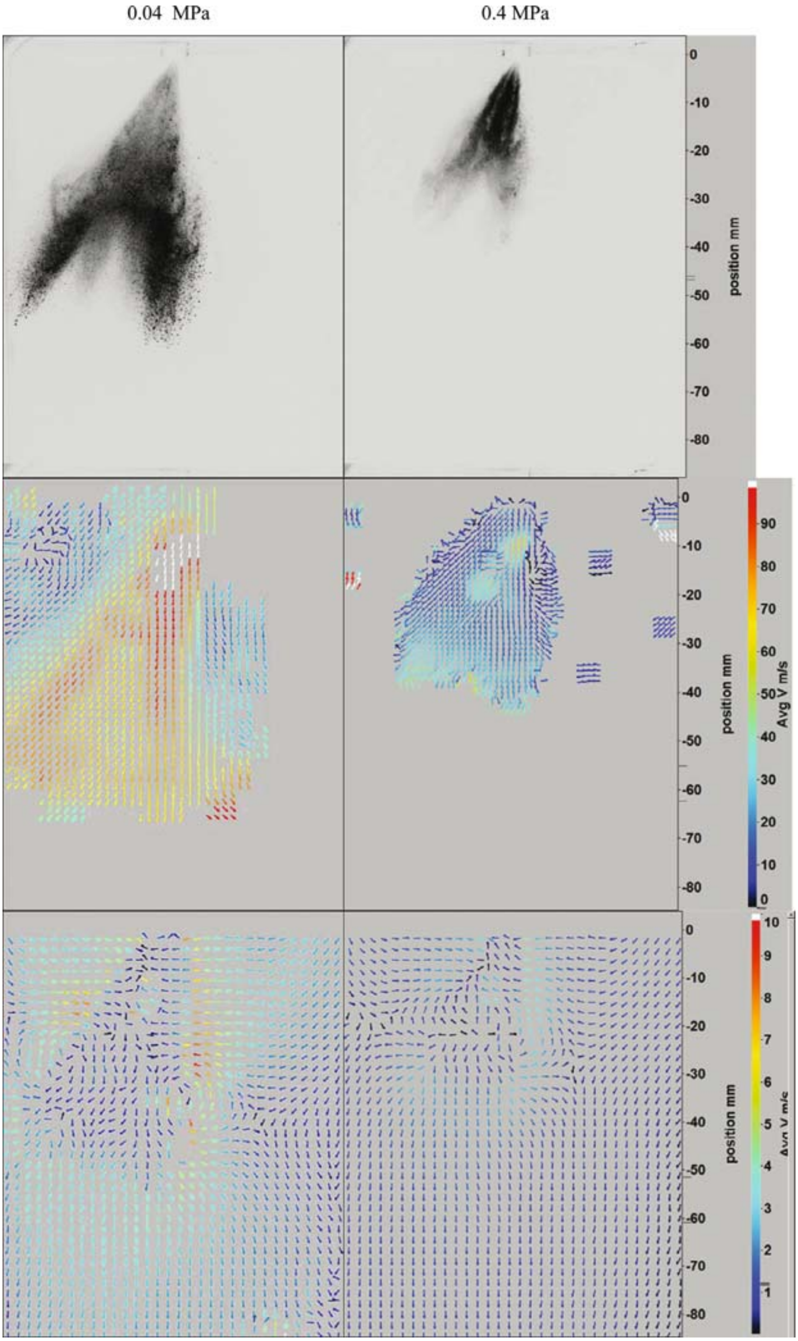

Fig. 5. Influence of the chamber pressure on fuel propagation: *top:* raw scattering images of the fuel jet, *center:* calculated fuel jet flow, *bottom:* calculated surrounding gas flow field

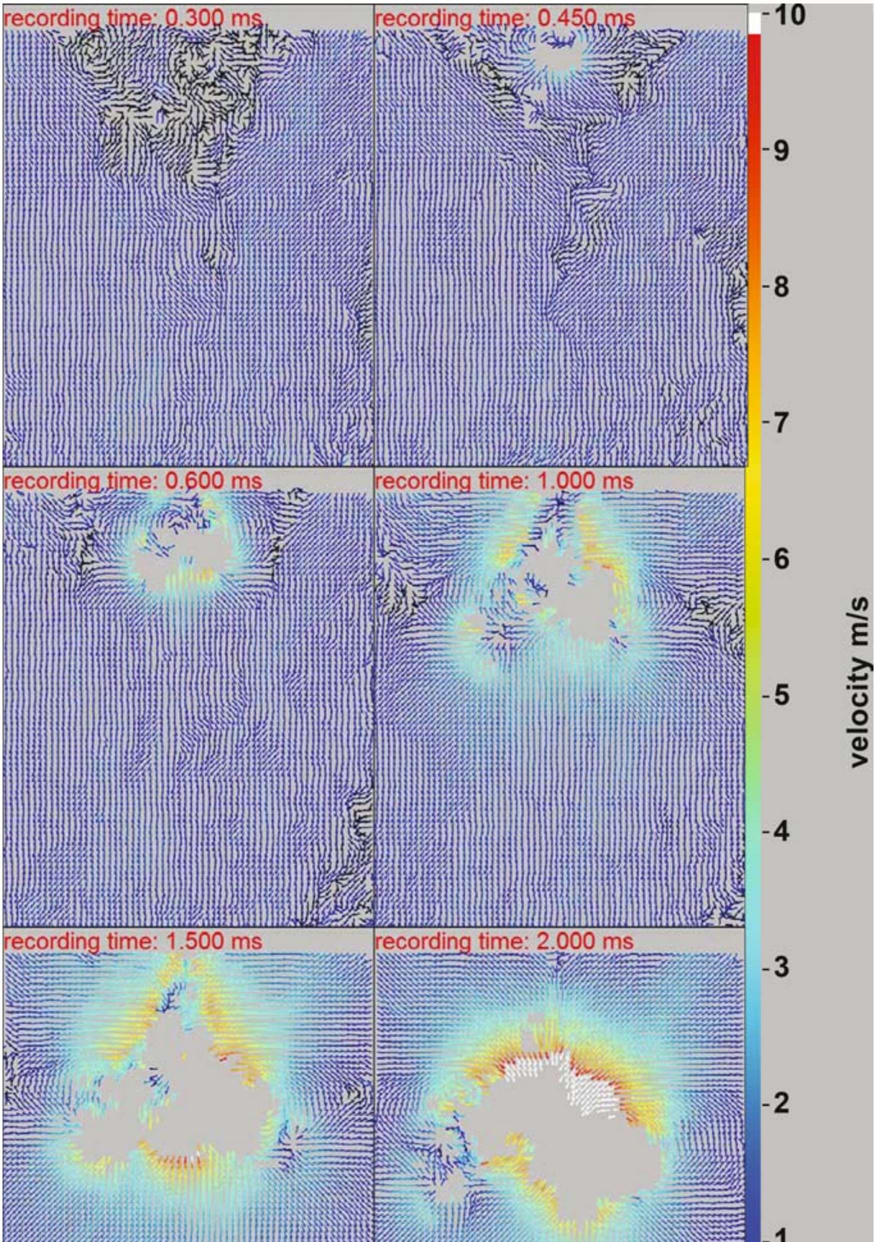

Fig. 6. Temporal evolution of the surrounding gas flow during the injection

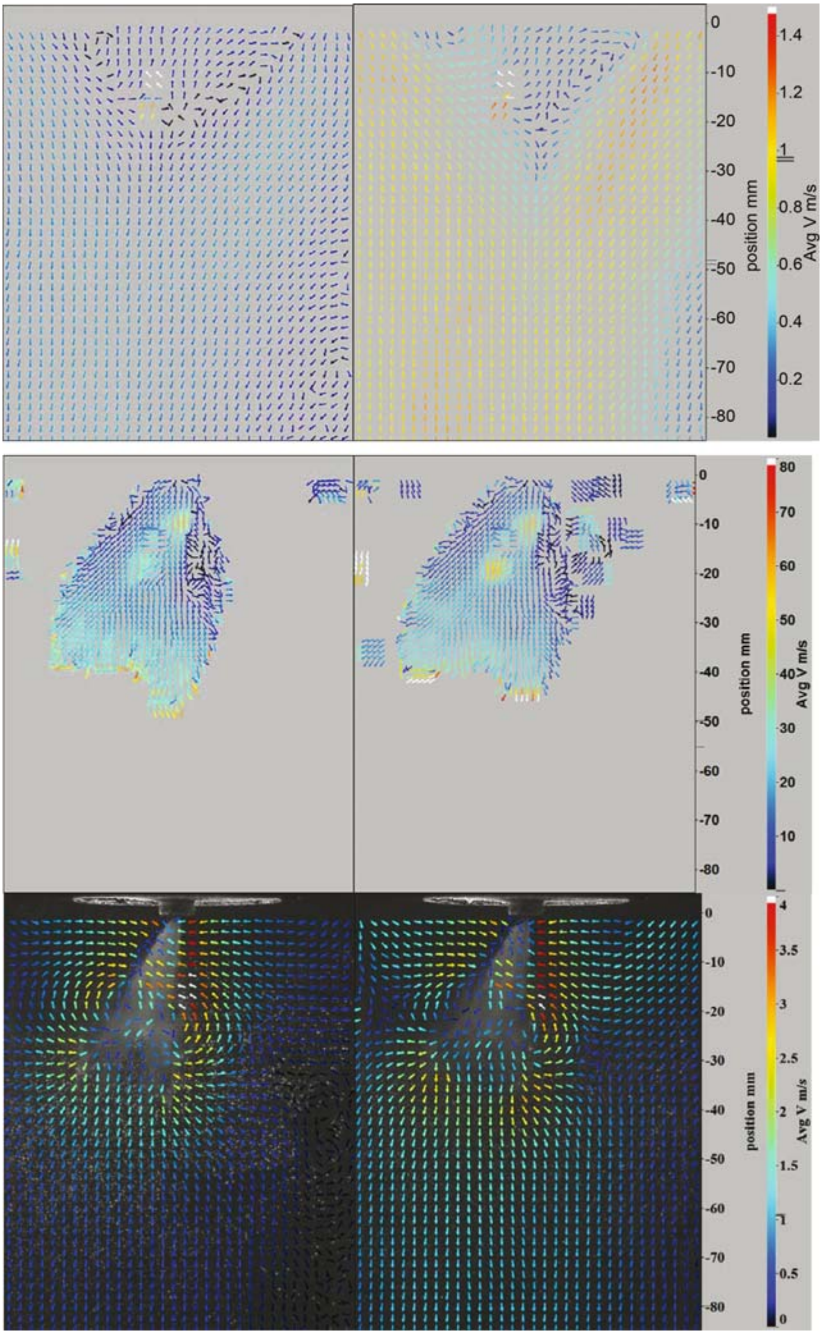

Fig. 7. Influence of the chamber air mass flow (*left side* $20\,m^3/h$ and right side $85\,m^3/h$): *top:* accelerated gas flow before start of injection, *center:* flow of the fuel jet, *bottom:* induced air flow

region below the spray that is not influenced by the injection. There, the velocities are higher for the greater mass flow.

This insight proves the applicability of the pressure-chamber investigations.

4 Conclusions

The two-phase PIV technique was successfully applied to the characterization of the air–fuel interaction and the building mechanisms of a burnable mixture using high-pressure injectors. The investigations were made in a pressure chamber and the results can be transferred to the improvement of direct-injection concepts for spark-ignited engines where mixture preparation is an essential step. Both fuel jet flow and the induced flow of the surrounding gas could be detected and analyzed.

The vortices that form at the boundary layer and the air-entrainment flow could be visualized. Many different operating conditions regarding temperature and pressure according real engine conditions and various injectors were investigated.

It could be shown that there is no influence of the scavenging air flow on the air–fuel interaction. The provided knowledge represents important input data for the modeling of injection processes and helps to design combustion processes.

For simultaneous measurement of both phases at least three pictures have to be taken using an image splitter, since there is no overlap in the possible time delays for the two phases.

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