

Particle image velocimetry of highly luminescent, pressurized combustion flows of aero engine combustors

Michael Schroll¹, Joachim Klinner¹, Lena Lange¹ and Christian Willert¹

¹ Institute of Propulsion Technology, German Aerospace Center, Cologne, Germany
michael.schroll@dlr.de

ABSTRACT

This contribution describes recent efforts leading toward the successful application of particle image velocimetry (PIV) in highly luminescent flames avoiding saturation of the second frame of commonly available double shutter PIV cameras, which is usually inevitable when using their interline-transfer CCD sensors. Information on fuel placement, reaction zone and temperature field among other quantities can be provided by frequently used spectroscopic techniques. The velocity information is of equal importance in providing insight into the convective transport of reactants and their products. This flow field data can be achieved by PIV using a dual sensor camera setup splitting the optical path with a beamsplitter cube. By exposing each sensor separately in the sub-microsecond range saturation due to flame luminosity can be sufficiently reduced to allow reliable measurement in pressurized combustion.

1. INTRODUCTION

In order to characterize the performance of modern aero engine combustors in correlation with emissions data, laser optical diagnostics are extensively utilized in specifically designed pressurized test rigs with good optical access. While spectroscopic techniques provide information on fuel placement, reaction zone, temperature field among other quantities, flow field data is of equal importance in providing insight into the convective transport of reactants and their products. The method of choice in providing this flow field data is particle image velocimetry (PIV). But the successful application of PIV in pressurized combustion imposes a variety of challenges. Among these, strong flame luminescence - mainly stemming from localized soot production and burn-off - can not be sufficiently suppressed with narrow banded laser line filters and result in the saturation of the second frame of commonly available double shutter PIV cameras. A useable solution to this problem is a dual sensor setup as shown in Fig. 1. The light is captured by a single objective lens and split into two optical paths using a 50/50 beamsplitter cube. With each sensor only active in the sub-microsecond range over the respective laser pulse with nanosecond duration, background light can be sufficiently suppressed to provide reliable PIV data.



Figure 1: Dual sensor PIV camera system with a large aperture medium format lens and remote focusing

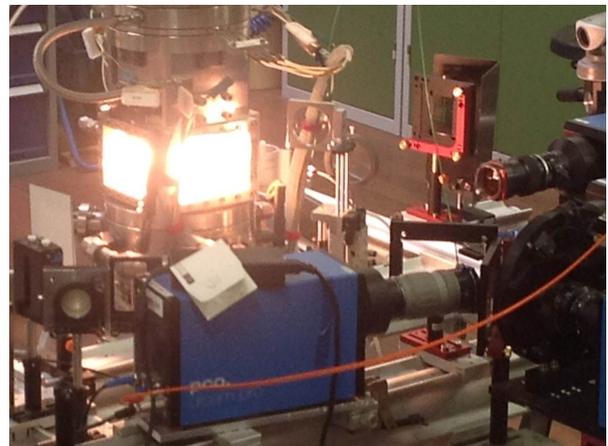


Figure 2: Spectroscopic imaging setup applied to pressurized combustor operating at "moderate" fuel loading conditions

The concept of beamsplitter based high speed electronic imaging was originally introduced in the early 1990's in order to achieve multi-frame imaging at burst frame rates up to 10^7 frame per second [1]. The basic idea was to trigger each sensor such that it was light sensitive only for the duration of a single pulse of a rapid sequence of light pulses. The technique was later applied to realize dual frame PIV imaging of high speed flows [2]. Even though this approach allows efficient suppression of ambient light it quickly became obsolete with the introduction of the frame-straddling technique of interline-transfer CCD sensors [3], but at the cost of extended exposure time of the second frame.

The application of PIV to reacting flows can nowadays be considered commonplace and is frequently used in combination with spectroscopic techniques for the study of turbulent combustion. Generally successful PIV measurements in combustion are limited to rather lean operating conditions with minimal flame luminosity [4]. On the other hand Figure 2 shows the bright shining pressurized operation of a kerosene fueled swirl nozzle at about 8 bar and about 1 kg/s mass flow where filters and shutters were found to be insufficient. The rather long readout time of order (50-200 ms) of the first frame from a state-of-the-art frame-straddling, double shutter camera has the undesired side-effect that the camera stays sensitive during this period which inadvertently (over)exposes the second image (Fig. 3). Common solutions to this problem have been the use of narrow-banded laser line filters and mechanical or electro-optic shutters [5,6,7]. Finite response times of the shutters and residual light transmission of the narrow banded filters reduce the effectiveness of these devices in very bright environments.

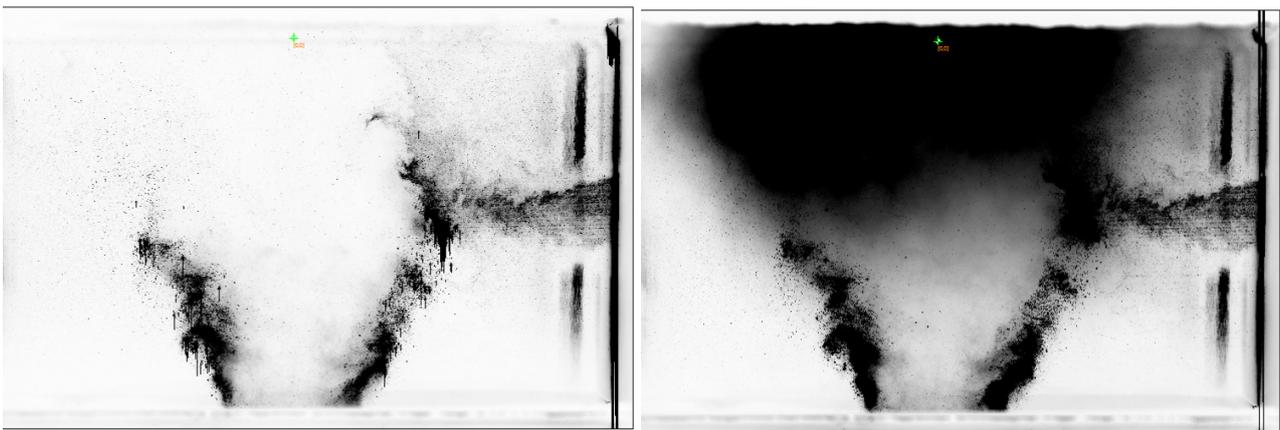


Figure 3: Inverted image pair obtained with standard double-shutter PIV camera (left: frame1, right: frame2) downstream of a swirl stabilized kerosene burner located slightly below the lower edge with quenching jet entering from the right edge (operating conditions: 5 bar plenum pressure, AFR 10)

2. EXPERIMENTAL SETUP

The motivation for the dual sensor camera system is motivated to reliably capture the flow field in highly luminescent flames inside pressurized combustor facilities. Several different swirl burners were investigated; each mounted inside pressurized single sector combustors (SSC), which are designed for the optical investigation of aero-engine combustors operating at realistic (flight relevant) conditions (Fig. 2). Measurements of kerosene-fueled combustion are performed at elevated pressures between 5 and 7 bar and preheated air in the range of 500 to 800 K. These SSC facilities, one shown exemplarily in Figure 4, have unobstructed optical access to the primary combustion zone from three sides, each using a combination of cooled pressure window and thin combustor liner window. A cooling film of preheated air protects the inside of the liner windows from thermal loading by the flame. The downstream end of the combustion chamber is closed off with a critical nozzle with which the operating pressure is controlled. The investigated burners typically are wall-flush mounted co-annular swirl nozzle systems with integrated atomizers.

The seeding material necessary for PIV in flames consists of porous silica spheres (SiO_2 , 0.5-1.5 μm size range) which is dispersed using a fluidized bed seeding device [5] as shown in Figure 5 and introduced into the facility's plenum upstream of the combustor. The seeder can be bypassed without changing the mass flow introduced into the facility which allows the seeding to be introduced only during PIV image acquisition phases. This prevents unnecessary deposition of seeding material on the windows and allows for longer operating times.

Figure 6 shows a typical arrangement for 2D-2C PIV to capture the flow field inside the combustion chamber using the dual sensor camera system. A perpendicular orientation along with window-normal light sheet introduction is generally chosen to keep reflections to a minimum [8]. Illumination is provided by a dual cavity PIV laser (Quantel) with a pulse energy of 120 mJ per pulse at a wavelength of 532 nm. To avoid particle loss by significant out-of-plane component

within the swirl flow the light sheet thickness is set at 0.8 mm. The light sheet formed by a combination of two cylindrical lenses of -25 mm and +200 mm focal length followed by a spherical lens with a focal length of 1000 mm and 50 mm in diameter. This diameter limits the height of the parallel light sheet to 50 mm. The third window allows the laser light sheet to transect the combustion chamber which reduces laser flare within the field of view. A programmable sequencer unit precisely synchronizes the laser pulses with the short camera exposures in the sub-microsecond range.

The dual sensor camera system is based on a pair of conventional scientific-grade CCD cameras with 2048x2048 pixel sensors (pco.2000). With both cameras operating in triggered, single-image mode, laser pulse 1 is matched to the exposure of camera 1 while laser pulse 2 is acquired by camera 2. This frame separation also must be ensured for very short pulse intervals where excessive exposure times result in inter-frame overlap and inadequate pulse separation. This can be guaranteed by placing the first laser pulse at the end of the exposure interval for the first camera with the second pulse placed immediately at the beginning of the second camera's exposure. With increasing pulse distances the second camera exposure interval is moved accordingly. In the present applications a camera exposure time of 500 ns and a laser pulse distance of 5 μs were found to be the best compromise for capturing the highly dynamic combustor swirl flow with strong out-of-plane component.

The dual sensor camera system (Figs. 1,6) uses a common lens with beam splitter cube to image a common field of view which has the advantage that inter-camera alignment is unaffected by changed lens focus. A medium format lens (Mamiya, 120 mm/f#2.8) is used since the back focal length of common 35 mm format lenses is insufficient to accommodate a 50 mm non-polarizing beam splitter and allows orthogonal placement of the two cameras without dismantling these. A motorized traverse in combination with a flexible bellows between lens and beam splitter provides remote lens focusing capability. A laser line filter (532 nm, +/-3 nm FWHM) ensured additional suppression of flame luminosity.

Because of the given limited light sheet height of 50 mm the regions of interest for both cameras were reduced slightly in height (ROI 250...1950 x 0...2048). Operating in the single image mode, in combined setting of two A/D converter and maximum pixel clock frequency (40 MHz), the camera frame rate can be matched to the laser's specified pulsing frequency of 15 Hz. This doubles the speed of data acquisition in comparison to standard PIV using the given camera and has the beneficial side-effect of better utilizing the limited operating time for PIV in combustor measurements.

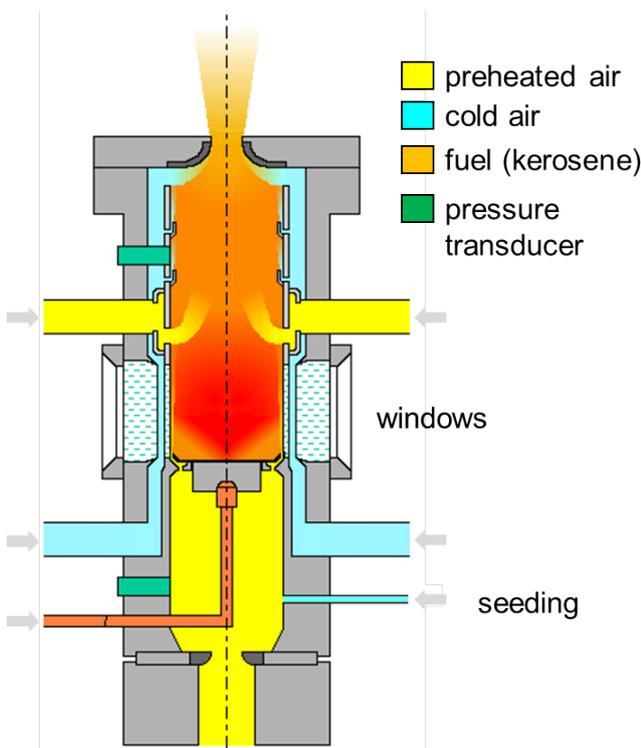


Figure 4: Schematic of the pressurized single-sector combustor (SSC) show in Figure 2

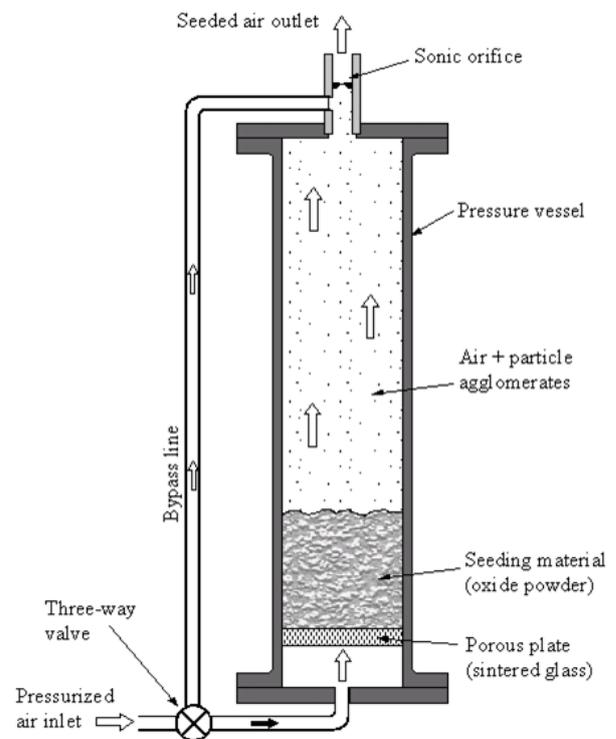


Figure 5: Seeding generator for solid particles using fluidized bed and sonic nozzle

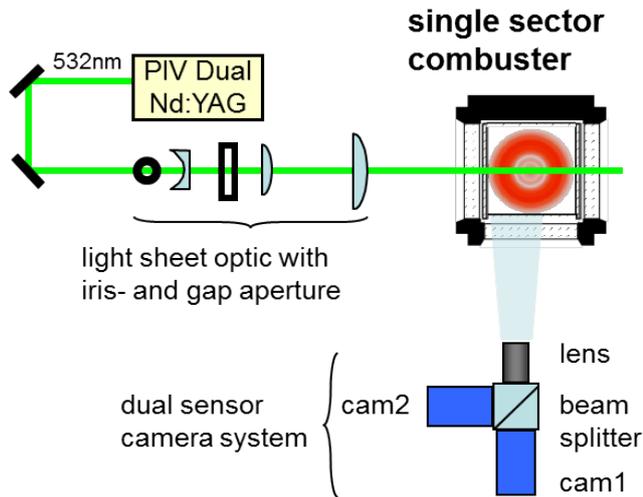


Figure 6: Optical arrangement for 2D-2C PIV at SSC

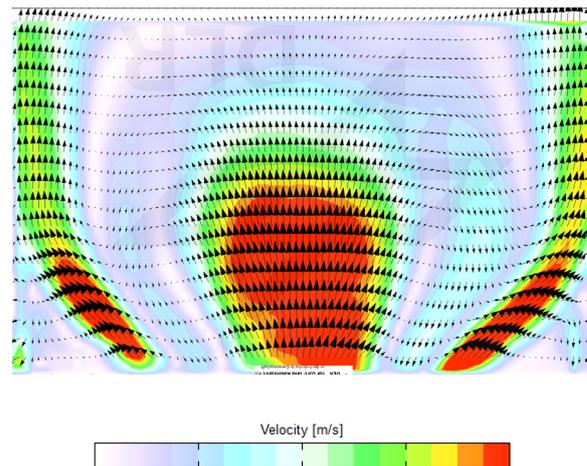


Figure 7: Instantaneous flow field obtained with PIV at ~ 7 bar with centered pilot flame and main flame as jets under 45° (vectors 2x down-sampled vertically)

3. INTER-CAMERA OFFSET CORRECTION

Because of the beam splitter configuration the registration of the two CCD array with respect to one another is of particular importance. While a perfect match is not feasible and - as will be described later - not even desired, a fairly precise registration is possible by mounting one of the two cameras on a micrometer translation stage. In addition, the cameras can be adjusted in height by wedges whereas a pivot mechanism allows to account for rotation with respect to each other. These efforts were made necessary because of manufacturing tolerances in sensor placement within each camera system and beam splitter placement result in offset of several tens of pixels. Even with this arrangement an a priori registration was found to be inappropriate because slight changes in temperature, vibrations and other extraneous influences introduced offsets exceeding several tenths of a pixel. As a consequence camera registration has to be applied in situ, ideally while the measurement data is being acquired.

Figure 7 shows a typical single sector combustor velocity field characterized by an outer recirculation zone in the corners and inner recirculation zone that is bounded by the central fuel spray and a 45° jet like flow that separates inner and outer recirculation zones. The strong out-of-plane component of the swirling flow and the high dynamics of the vector field require a short pulse distance in virtue of which a considerable part of the flow field ends up only in a very small particle displacement. Looking in detail the velocity field seems to be slightly unsymmetrically in opposite direction for the central fuel spray and the 45° jets. Considering combustors often uses counter rotating swirl flows for optimized spray distribution this asymmetrical velocity field becomes comprehensible. Unfortunately stereoscopic PIV approaches in the combustion chamber under high pressure are not feasible and since the third component remains unknown. To reduce the influence of strong out-of-plane component in the outer regions, the optical axis of the lens was moved in subsequent measurements to coincide with the region of the strongest out-of-plane motion present near the main jet which reduces the influence of the perspective error on the measurement. In this off-axis arrangement it is no longer possible to record the entire combustor flow field, but allow one half of the nearly symmetric flow field to be recorded more reliably data with increased spatial resolution.

In the area of recirculation between the pilot and main flame the particle displacement is mainly below one pixel. Even smallest errors in the inter-camera registration significantly influence the final result. Registration errors influence the determination of flow geometry aspects such as stagnation flow points, location of dividing stream lines and the position of the reversal zone between the pilot and main flow, all of which are great importance for the characterization of combustion chambers. As these features arise as velocities or components thereof tend toward zero, small errors in the camera registration significantly affect the accurate determination of the flow features which ultimately can lead to misinterpretations of important metrics.

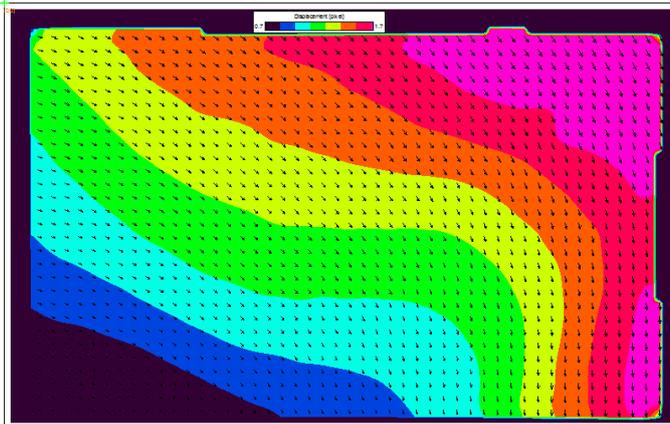


Figure 8: In-situ inter-camera registration determined by simultaneously recording particle images; offset between 0.7 and 1.7 pixel



Figure 9: Static random dot pattern for inter-camera registration.

Inter-camera registration can be achieved in several ways. Given that geometric calibration is nonetheless required for converting pixel displacements to velocity data, this registration could be realized using the calibration target itself. Using individual mapping functions for each camera it is possible to map the image data to a common grid following a common approach used for stereo PIV. In the present case this method proved to be unsuitable, in particular because it requires the placement of the suitable, sensor-filling calibration target in the field of view within the combustion chambers, which generally is only possible after extended facility cool-down and dismantling.

The second approach toward sensor registration is based on simultaneously acquired particle image data by both cameras with the inter-pulse separation identical to zero. This approach can be applied in situ and only requires a minor change in the camera laser triggering sequence. The recovered map of particle offsets between both images in principle describes the misregistration of the sensors with respect to each and only needs to be subtracted from the actual measurement data to obtain the true flow field. A sample registration map obtained by this approach is shown in Figure 8 but was found not to be representative of the actual misregistration, typically a linear translation and slight rotation. More detailed analysis revealed that biasing effects such as “peak locking” distort the registration data in particular if the offset between the sensors only has a few pixels of variation across the field of view. The sharply focused particle images themselves barely meet the minimum required particle image diameter of ~ 2 pixel and compound the problem of peak locking.

The most reliable sensor registration maps could be achieved using (near) simultaneous recordings of a rather coarse random dot pattern such as shown in Figure 9. For this purpose, however, the pattern must be placed in the measurement plane and the exposure sequences of both cameras have to be changed completely to achieve sufficient exposure of the image using indirect illumination of the dot pattern. Placement of the pattern inside the combustion chamber is not possible and requires that the entire camera system is traversed to position the focal plane to an externally accessible position.

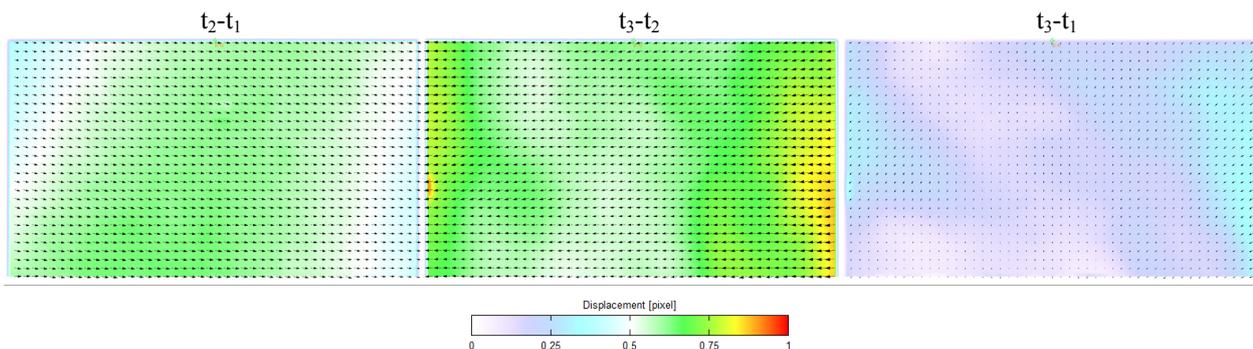


Figure 10: Differences between camera-offsets in a long time series

The review of the long-term mechanical stability of the two-camera setup nonetheless revealed a weakness of this approach. Three dot pattern image pairs were recorded: before (t_1) and after the measurement a few hours later (t_2), and then again after 16 hours (t_3). Deviations between the maps are visualized by subtracting the maps from each other (Figure 10). Here it is quite apparent that the difference between the maps obtained at (t_1) and (t_3) is minimal (below 0.25 pixel) which can be attributed to the fact that the camera system is in an ambient condition. On the other hand the image pair acquired at (t_2) after the camera system has been exposed to the warm environment of the operating combustor facility. Apparently, the thermal radiation of the combustion chamber causes considerable but reversible material expansions of the camera system on the order of 3-4 μm (pixel pitch is 7 μm). During facility operation this offset may even be different due to sound pressure levels in excess of 110 dB which makes it necessary to acquire the random dot pattern registration images under the same operating conditions as the actual flow field data. As mentioned above, it is not possible to place the speckle pattern in the light sheet plane during the measurement. A viable solution is to set up the target in the same distance outside the combustion chamber and display to the cameras by a lower able mirror before and after each measurements series. Any inaccuracies in the positioning of the mirror are not important because they are the same for both cameras and do not affect the camera offset determination.

Another lesson learned is that a nearly perfect alignment of both cameras has a significant drawback. Alignments like this often fits in one point close the center and rotates slightly around this “origin” with very small camera offsets below 0.5 pixel over a large region of the image as shown in Figure 11. But smaller offsets especially below 0.1 pixel approach the uncertainty achieved by the cross-correlation algorithm itself. If this calibration region overlaps with the recirculation zone, a region of lower velocities and therefore only small particle offset, correlation algorithms inaccuracies interact and get multiplied. In practice it was found that having as misalignment of several pixels (>5 pixels, Fig. 12) improved the overall data quality.

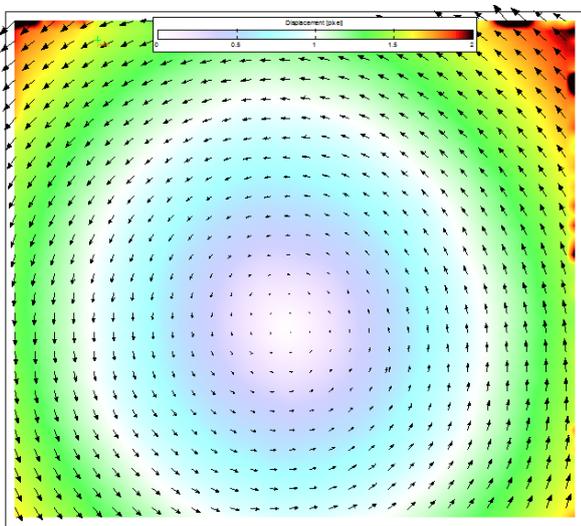


Figure 11: “seemingly” perfect camera-offset between 0 and 2 pixel

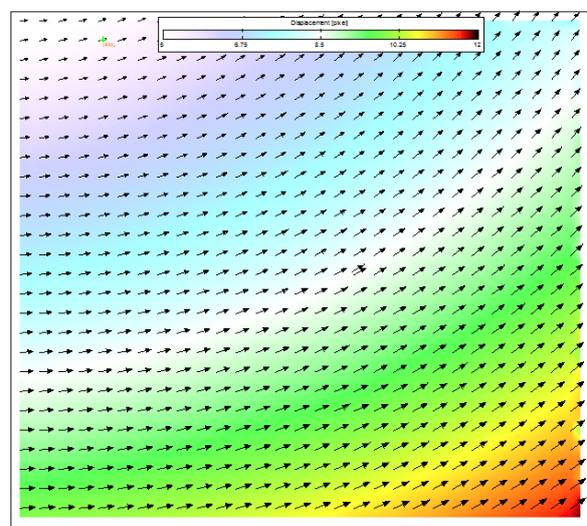


Figure 12: more stable camera-offset between 5 and 12 pixel with outboard rotation origin

Incorporating the lessons learned while working with the dual sensor PIV setup in rough environments during the first measurement campaigns on the single sector combustors resulted in a reliable list of operating procedures that were observed in following campaigns in the SSC on different burner configurations. The improved random dot pattern calibration procedure is used and the optical axis is shifted to intersect with the area of highest out-of-plane component to reduce measurement uncertainties due to perspective distortion. Figure 13 illustrates the uncorrected vector field obtained by processing the acquired particle image pair. Subsequent subtraction of the sensor misalignment reveals the velocity field downstream of the fuel injector (Figure 14). Even if the jets from angular pilot and main injector are already visible in Figure 13 the complete flow structure and especially the expansion of the recirculation zone and its dividing streamline is only recognizable after camera offset subtraction (Fig. 14). Finally PIV could be improved successfully as application in highly luminescent kerosene fueled flames for future flow field investigation in combustors.

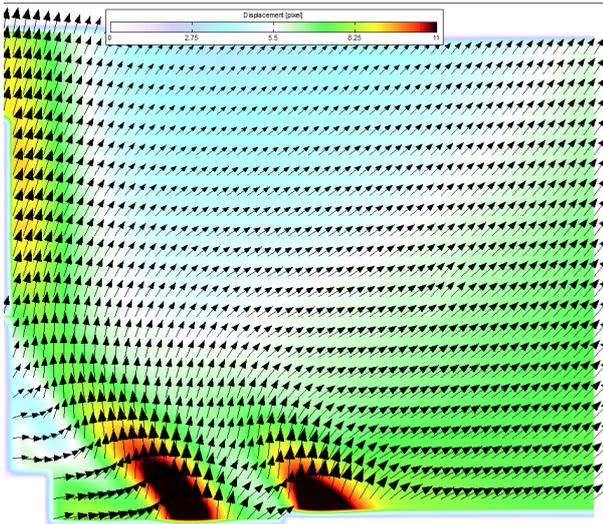


Figure 13: Intermediate field of particle displacement acquired with the dual sensor camera system prior to sensor offset correction

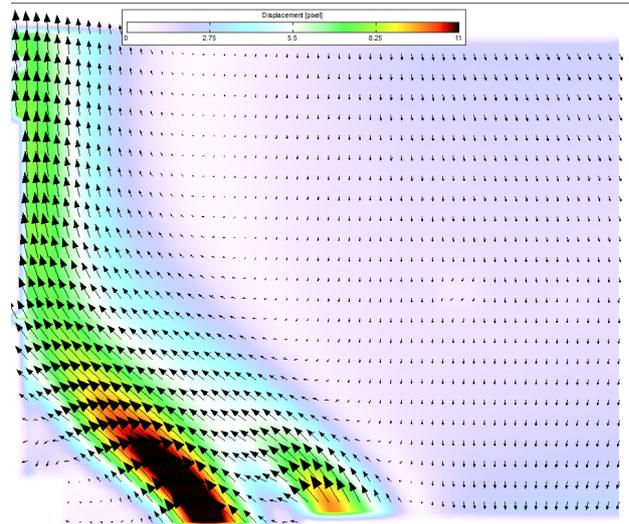


Figure 14: Actual displacement field after sensor offset correction

4. FLOW FIELD ESTIMATION BY SOOT-TRACKING

Further analysis of the acquired image data of the highly luminescent combustor flow revealed that in addition to Mie scattering provided by illuminated particles and droplets, Rayleigh scattering by laser illuminated soot particles is captured as well. Figure 15 shows a representative image obtained in the flow field of a pressurized combustion chamber with the swirl nozzle located near the middle on the lower edge and mean flow propagating from bottom to top. Exposure time of the sensor is 500 ns while the laser light pulse has a duration of ~ 5 ns. The image is characterized by four types of light scattering: (1) from the glass liner walls left on the left and right edges, (2) Mie scattering by the dense fuel spray immediately downstream of the fuel nozzle, (3) Mie scattering by the inert seed particles ($1 \mu\text{m}$ porous silica spheres) and (4) Rayleigh scattering by soot particles in the fuel rich combustion zones. The highly turbulent flow downstream of the fuel injector results in very finely structured soot patches that have the potential of serving as flow markers in place of seeding particles. This would, in principle, allow a rough estimation of the flow field without the need of adding particles, prolonging the effective time for facility operation as window contamination due to particle introduction is reduced.

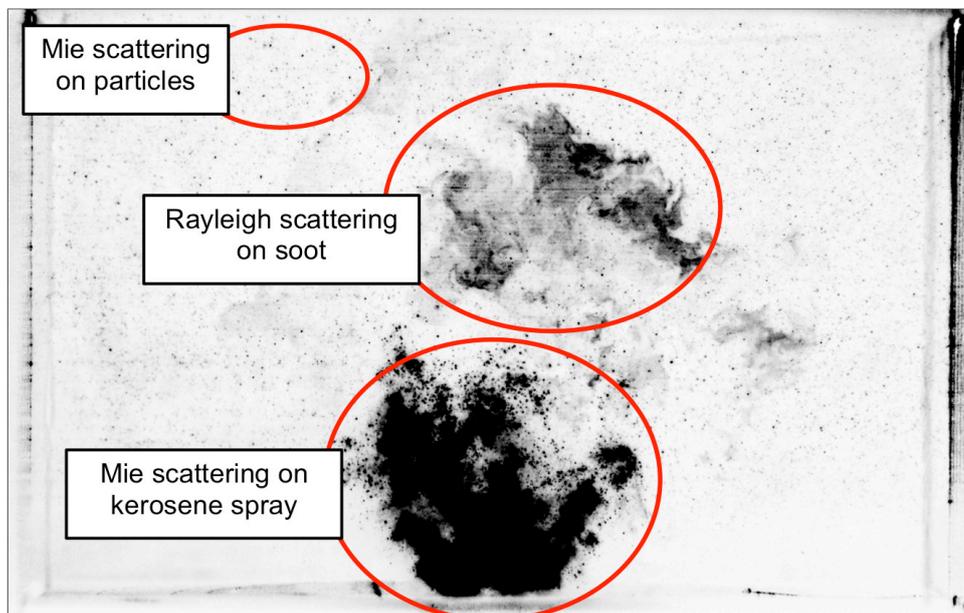


Figure 15: Single recording of the reacting flow field downstream of a kerosene swirl atomizer located at the bottom center at 6.7 bar plenum pressure

Figure 16 shows eight randomly selected images of the dual sensor camera system consisting of a series of measurements at a different AFR of 55 at 6.7 bar obtained without PIV particle seeding. At this operating condition the area downstream of the spray cone is dominated by stochastically appearing patches that are formed by light scattering from soot (Rayleigh scattering). Due to the fine structure of the soot patches conventional PIV cross-correlation processing is applicable. The average intensity distribution of these soot patches shows a high frequency of soot occurrence in the area above the fuel spray cone. At same time there is an absence of signal in the bottom left and right corners of the images which contain the outer recirculation zone. Clearly these regions will not provide any displacement information.

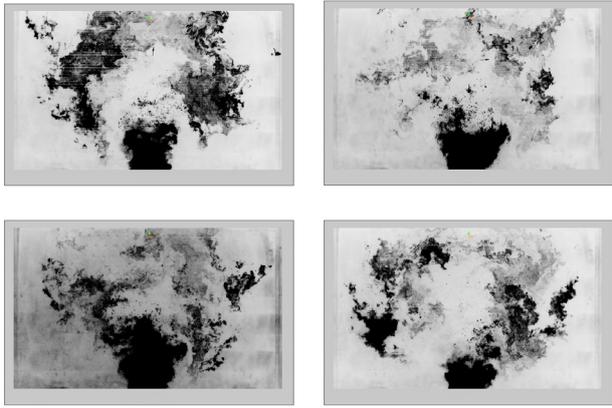


Figure 16: Random PIV recordings (first frames only) acquired at 6.7 bar, AFR55 with kerosene spray cone from the swirl atomizer located at the bottom center; other patches are clouds of soot visualized by the laser light sheet (Rayleigh scattering)

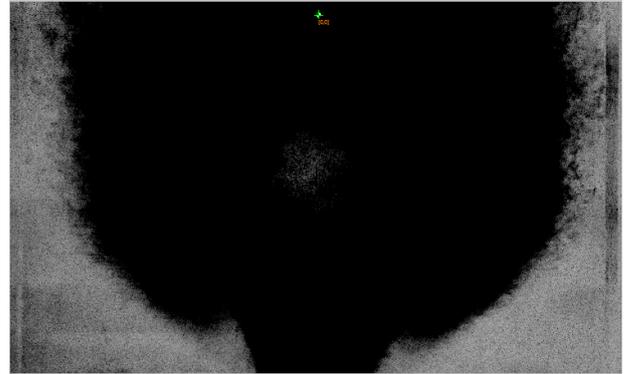


Figure 17: Averaged soot and spray distribution at 6.7 bar, AFR55 at centered light sheet position $r/R=0$

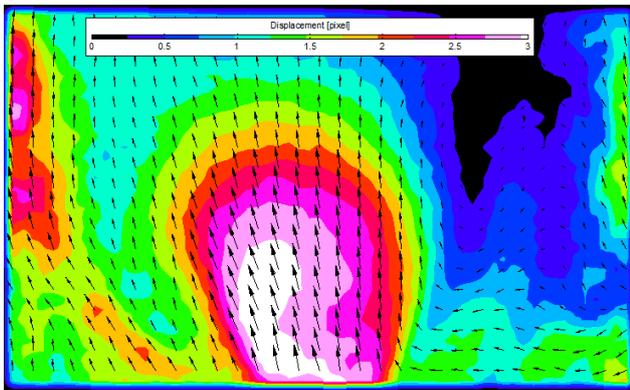


Figure 18: averaged vector field of displacement based on soot pattern only; 6.7 bar, AFR55, $r/R=0$, $n=400$

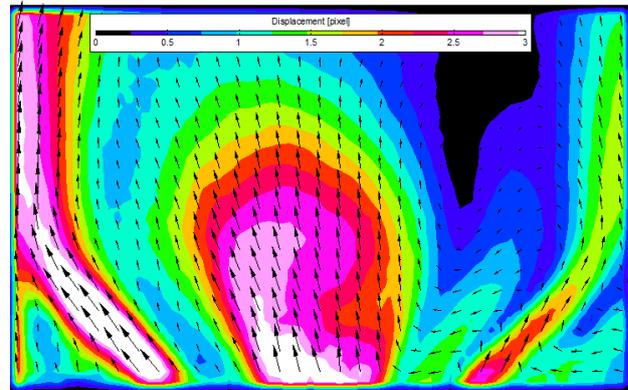


Figure 19: averaged vector field of displacement based on soot pattern and seeding particles; 6.7 bar, AFR55, $r/R=0$, $n=400$

The mean displacement field obtained by processing the particle-free, soot/spray images is presented in Figure 18 and put into reference to PIV data that was acquired with particle seeding at the same operating conditions (Figure 19). Both data set represent ensemble averages of $n=400$ individual PIV recordings. The difference of the vector maps is provided in Figure 20. Significant differences are apparent for those areas with little or no soot presence such as the outer recirculation and the external cone of swirling jet flow. Agreement is quite favorable in the interior recirculation zone where soot patches have their highest frequency of occurrence. The velocity in the area near the liner walls is underestimated as well by the soot tracking images which can be explained by the fact the soot patches can only reach this area when the confining swirling jet flow is locally interrupted. It should be noted here that the asymmetry in Figures 18 and 19 is due to the inadequate offset correction as this data was acquired without dot-pattern offset correction procedures.

5. CONCLUSIONS

The presented material describes recent efforts dedicated toward extending the applicability of PIV toward highly luminescent pressurized combustor flows. The long integration time of the second frame of conventional dual-frame PIV cameras makes current dual-frame camera technology unsuited for the present applications and motivated a dual-sensor configuration which had been in use prior to the appearance of dual-frame PIV cameras in the mid 1990's.

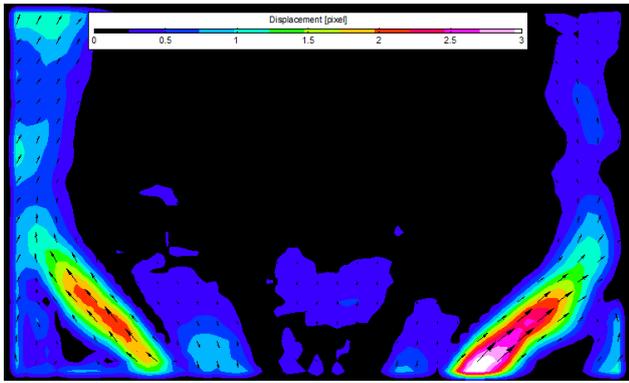


Figure 20: Remaining vector field out of subtraction between seeded and not seeded series; $r/R=0$

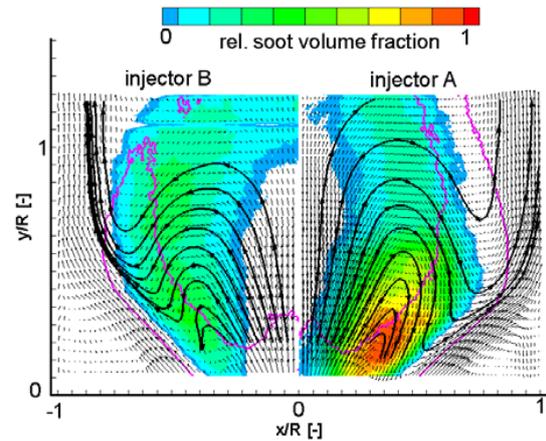


Figure 21: Velocity field and soot distribution (false color) for two different injectors A and B. Magenta contour lines show heat release regions [9]

Limiting the sensor exposure times to very short durations of 500 ns sufficiently suppresses flame luminosity and allows to reliably capture the pulsed laser light scattered by the seed particles. Mechanical tolerances in the camera module along with the presence of a beam splitter in the optical setup necessitate an inter-sensor offset correction. After several iterations procedures for proper in-situ offset corrections could be established and ultimately allowed successful PIV measurements in highly luminescent environments.

Depending on the operating condition and injector geometry soot patches arise in the combustor flow that are visualized by the laser light sheet (Rayleigh scattering). Due to their fine structure these patches serve as flow markers and be tracked with conventional PIV processing algorithms. The comparison of “flow” fields obtained with and without particles revealed that the soot patches do not adversely affect the velocity estimates provided by the seeding particles. Soot tracking therefore is a promising alternative when the particle image signal is lost in flows with higher soot fractions.

The availability of flow field data from highly luminous combustor flows is considered an important step in applied research on combustion technology. In combination with spectroscopic techniques detailed investigations on soot production, distribution and transport in the different combustion zones are of particular importance for current research projects (Fig. 9) and has been a breakthrough for the ability to understand the influence of design features on soot formation [9].

6. ACKNOWLEDGEMENTS

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