Flying PIV measurements in a 4-valve IC engine water analogue to characterize the near-wall flow evolution

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Abstract. For a deeper understanding of the highly unsteady near-wall boundary layer flows in internal combustion (IC) engines, PIV-based flow field measurements close to the inner cylinder and piston walls within transparent engines are required. The herein described flying PIV method in combination with a scanning light-sheet provides time-resolved PIV measurements in a transparent IC engine water analogue in a radial plane 1.5 mm apart from the planar piston crown while the piston is moving. The light-sheet is parallel to the piston surface and moves with the piston thanks to the scanning technique that synchronizes the sheet motion with the non-linear piston motion. A compact high speed camera is positioned within the piston shaft below the transparent piston head and records the particle fields within the illuminated plane in time-resolved manner. The measurements are realized in a water-analogue of a 4-valve engine at 950 rpm engine speed in real situation. Instantaneous pictures are compared to phase-averaged velocity maps and allowed to localize regions of high cycle-to-cycle fluctuations.

1. Introduction

The in-cylinder flow mixing and combustion processes strongly depend on the flow interaction and heat transfer with the inner walls, i.e. the cylinder head, the cylinder walls and the piston crown. Formation of hydrocarbons, carbon monoxide and soot is highly influenced by these near-wall boundary layer flows. One possible trend towards decreasing fuel consumption at same power is to downsize the engines and use a smaller bore. This goes with an increase in the ratio of total surface area to chamber volume. Therefore near-wall processes get of higher relevance for efficient generation of power density. To understand the underlying physical processes in these regions requires the ability to measure the flow field in IC engines close to the boundary layer of the piston. New measurement technologies need to be developed that are able to record the flow and temperature field close to these moving walls in time over the whole cycle. Such a new technology is presented herein which uses a scanning light-sheet and a co-moving compact high-speed camera integrated within the piston shaft, both synchronized with the piston motion. This was only possible because of the nowadays super-compact sizes of high-resolution CMOS cameras. Typically, these cameras are also useful for Time-Resolved PIV (TR-PIV) systems which made large progress towards successful

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application in IC engine flows in the recent years. Borée et al. investigated the spatial structure of the flow and its temporal evolution during a series of consecutive cycles via TR-PIV in a research engine of moderate tumbling ratio [1]. They also studied the flow details during the intake cycle to understand the cause of cycle-to-cycle fluctuations in the intake phase, see Borée et al. [2]. However, it is only recently that Volumetric PIV measurements or Tomographic PIV (Tomo-PIV) could be realized within transparent engines. In-cylinder measurements of the instantaneous 3D flow in the cylinder of a four valve internal combustion engine were done by Overbrüggen et al. using holographic particle image velocimetry [3]. Tomo-PIV measurements within a fat light- sheet of 6 mm thickness were presented by [4]. In addition, scanning PIV was applied for a 2-valve [5] and a 4-valve engine flow [6], those measurements were so far only possible under reduced engine speeds at maximum 950 rpm. Nevertheless, the measurements clearly revealed the curved “U”-like shaped core of the tumble vortex which is due to the interaction of the tumble flow with the cylinder walls [3, 6]. However, so far none of the methods could show the temporal evolution of the near-piston flow in high spatial and temporal resolution which is the aim of the present work.

The system developed in our lab is based on a compact, inside the piston-shaft mounted camera and a motion-synchronized scanning light-sheet method. This allows us to investigate the evolution of the near-piston flow topology and to distinguish regions of high wall-shear or flow separation due to the interaction of vortices or the tumble flow with the piston wall. Those are important to understand the generation of hot spots, see Hasse et al. 2010 [7]. The article is organized as follows. First, the optical four-valve research engine is described in detail in chapter 2. In addition, the scanning system to generate the co-moving light- sheet is specified. Thereafter in chapter 3 results are given in form of instantaneous vector fields from TR-PIV measurements at the piston wall. A number of successive cycles allowed us to deduce cycle-to-cycle variations in position and motion of the vortices next to the piston wall.

2. Experimental Set-Up & Methods

The experiments were carried out in a transparent version of an original 4-valve cylinder head with a displacement of 1.6 liters (BMW Prince 2), see figure 1.

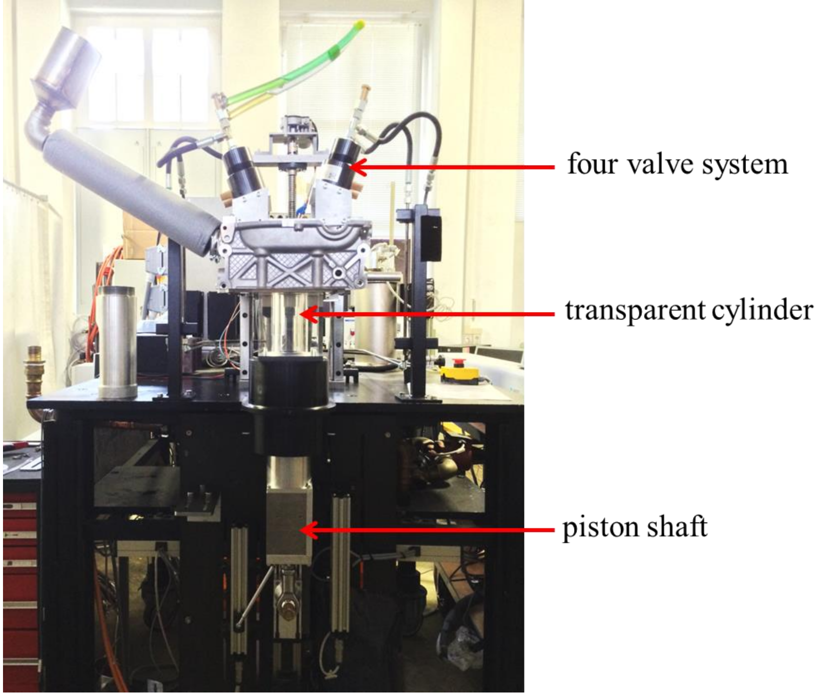

Figure 1. Picture of the experimental set-up (left) of the 4-valve engine (BMW Prince 2) with transparent cylinder. The high speed camera is integrated in the piston shaft that is moving down in the intake cycle.

Table 1. Engine characteristics [8].

Bore	76.5 mm
Stroke	85.8 mm
Valve-Stroke	9 mm
Clearance	6 mm
Piston Speed	0.15 m/s
Engine Speed	950 rpm
Working Fluid	Water
Temperature	323 K
Density	0.98×10^3 kg/m^3
Kinematic viscosity	0.55×10^6 m^2/s
Re	21000

The engine conditions under investigations are given in table 1. The working point represents the engine at a running speed of 950 rpm and the Reynolds-number is about 21000 defined with the piston speed and bore. The transparent piston made from Perspex has a plane piston crown and floor. This allows to record the flow in the cylinder from below the piston. Of interest in this study is the flow in a radial light-sheet plane parallel to the piston head and above it with a certain offset. Therefore a compact high-speed camera (Mikrotron Cube4, resolution 1020×1020 px² at a maximum of 1000 fps) is mounted in the piston shaft below the piston crown and moves with the driving shaft. Prior to the experiments, the focus of the camera lens is set to achieve sharp particle images in the radial plane which is illuminated with a light-sheet generated with a pulsed Nd:YLF laser (Litron Nd:YLF, 30 mJ at 1 kHz repetition rate, wavelength 527 nm) and equipped with a light-sheet optic in front of the light arm.

Thanks to an optical light-sheet scanning system using a rotating polygonal mirror (20 facets), the light-sheet can follow the piston in vertical motion. First, this ensures that the particle images remain in focus over the whole intake cycle. Second, this requires a special timing of the laser-pulse with the rotating polygon mirror and encoding with the actual piston position. Both can be programmed in such a way that the light-sheet position remains always at the same offset relative to the flat piston head while the piston is moving (Flying PIV). The offset of the plane relative to the piston head can be set individually by positioning the whole optical setup with a traverse along the vertical axis.

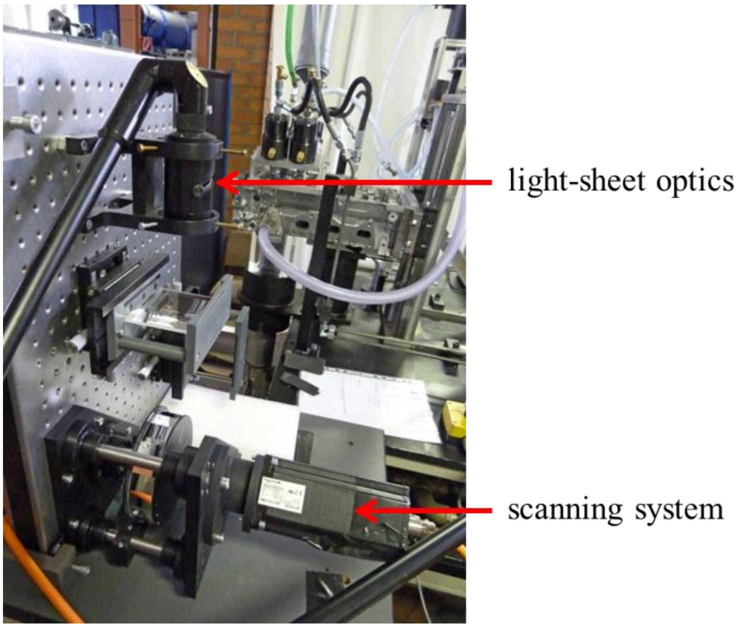

Figure 2. Picture of the light-sheet scanning system with the light arm, both Relay lenses and the rotating polygon at the bottom

The principle of the flying PIV system is given in figure 3. When rotating the polygon, the light-sheet moves in a parallel way through the cylinder thanks to a symmetric pair of cylindrical Relay lenses (*f*=200), see figure 4. A special counter-sequencer is programmed and generates the pulse-timings to the single positions on the facets in a free-programmable way. For the application of this technique to follow the piston motion, the sequencer is programmed with the harmonic time-course of the piston motion. The rotation rate of the polygon is set such that the center frequency (passage of facets per unit time) is constant 900 Hz. While the polygon is rotating at constant speed, the most upper light-sheet position near TDC is generated with a laser-pulse that leads relative to the center frequency such that the pulse is given at the leading edge of a facet (Fig 4A). The center plane (Fig 4B) is generated with a laser pulse given at the moment when the center of the facet passes the beam, so the shift relative to the center frequency is zero. Finally, the light-sheet at BDC is generated with a certain delay to the center frequency such that pulse is given at the trailing edge of a facet (Fig 4C). Thus, by varying the pulse shift relative to the constant center frequency we are able to shift the sheet relative to the center position in an arbitrary manner. The maximum vertical span with the given lens system between the outermost planes at TDC and BDC equals the stroke of 85.8 mm.

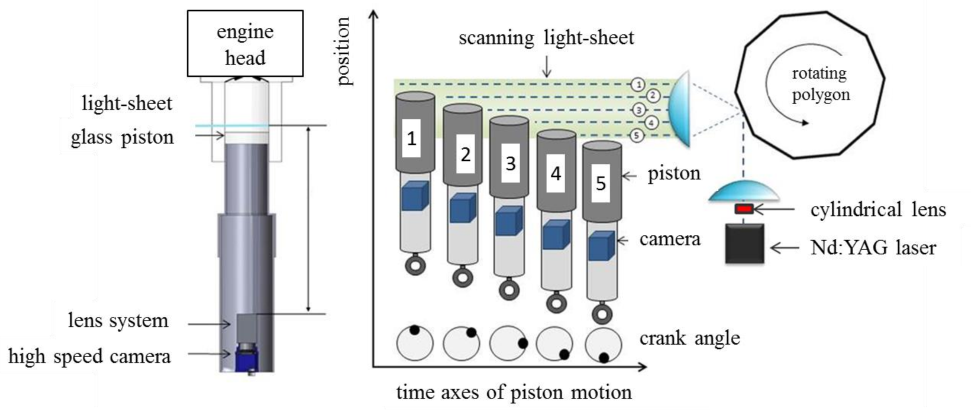

Figure 3. Transparent piston with inside-the-shaft mounted high-speed camera that moves during the intake stroke with the piston downwards. A light-sheet scanning system moves the light-sheet parallel to the piston and at constant focal distance to the lens.

To ensure that the light-sheets plane remains parallel to the surface plane of the piston, a set of two Relay lenses is used which are set with their focal plane on the surface of the polygon. Therefore the angular deflection of the light-sheet on the facets of the polygon is reconfigured into a parallel shift of the sheet, see figure 4.

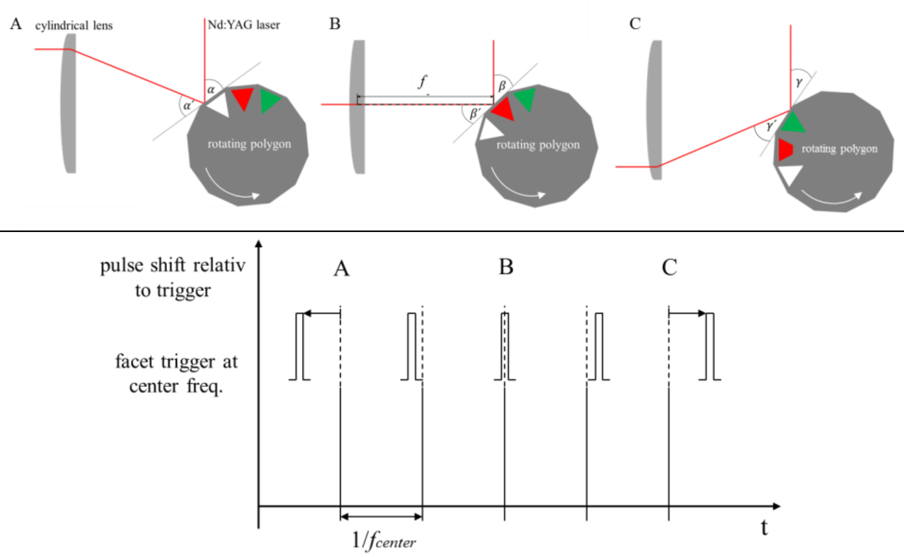

Figure 4. Schematic description of the cylindrical lens to reconfigure the angular deflection into a parallel shift of the light-sheet. The cylindrical lens is positioned in focal distance *f* to the facets of the polygon. A) light-sheet position at TDC, B) in the centre of the cylinder and at BDC C) and corresponding pulse timing diagram (bottom)

To start the recording sequence the piston is positioned in TDC-position and the rotating polygon gives trigger signals by a displacement sensor to the sequencer. The sequencer controls the rotating polygon and the single positions of the facets while the experimental set-up is waiting for the main start trigger. This main signal controls the start of the piston and the opening of the valve-system as well as the laser pulses and the recording of the high speed camera in sync-mode. Note that at constant rotating speed of the polygon, the presented technique results in a small variation of the inter-time between successive laser pulses to shift the laser-pulse relative to the facets, which however is easy to correct for in the post-processing of the PIV images. The variable pulse timing is considered when the sequences of the images are processed and velocities are determined by the ratio of average particle shift in the interrogation window over the actual time span between successive images.

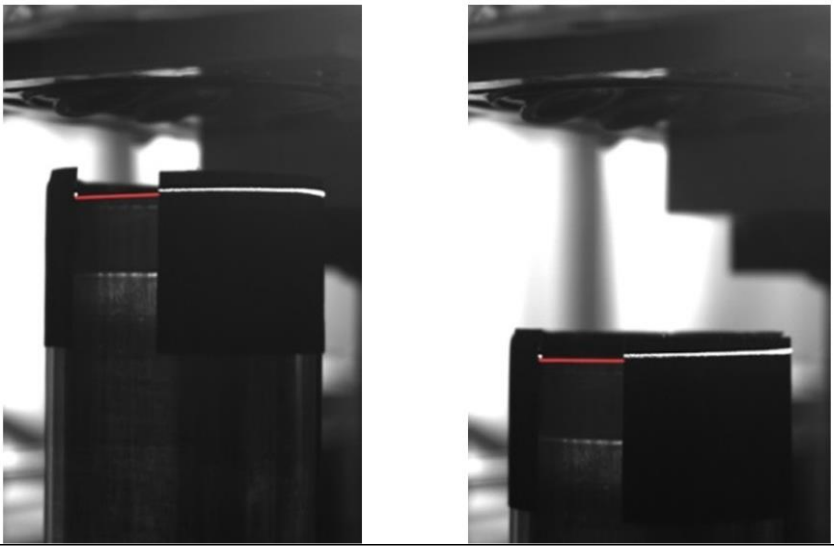

Figure 5. a) pictures of the reflection of the light-sheet (white line) on black paper wrapped around the piston crown at two position of the piston within the intake cycle; the red line marks the upper edge of the piston head.

The quality of the timing was controlled by measuring the light-sheet position during the motion cycle of the piston in a typical intake cycle. Therefore, the piston was covered with black paper to see the reflections of the laser sheet, see figure 5a. Both the reference edge of the piston head and the light-sheet position are captured during the motion cycle with an external high-speed camera looking from the side.

The profiles in figure 5b display the vertical position of the moving light-sheet and the piston head during the intake cycle. As seen from the profiles, the light-sheet (e^{-2} thickness of $w \approx 1.5$ mm) always remains in nearly constant distance relative to the piston with an average distance. A closer look into the distance profile is given in figure 6. The average distance is about 1.5 mm and deviations from the average are less than 0.4 mm within the complete cycle. Those are maximum only in the beginning of the intake cycle and are caused by a non-perfect alignment of the 2nd Relay lens. Near the TDC the light-sheet is near the edge of the lens where distortion effects become significant. In addition, partly the jitter is a results of the uncertainty in the edge detection algorithm used for processing the sideview images.

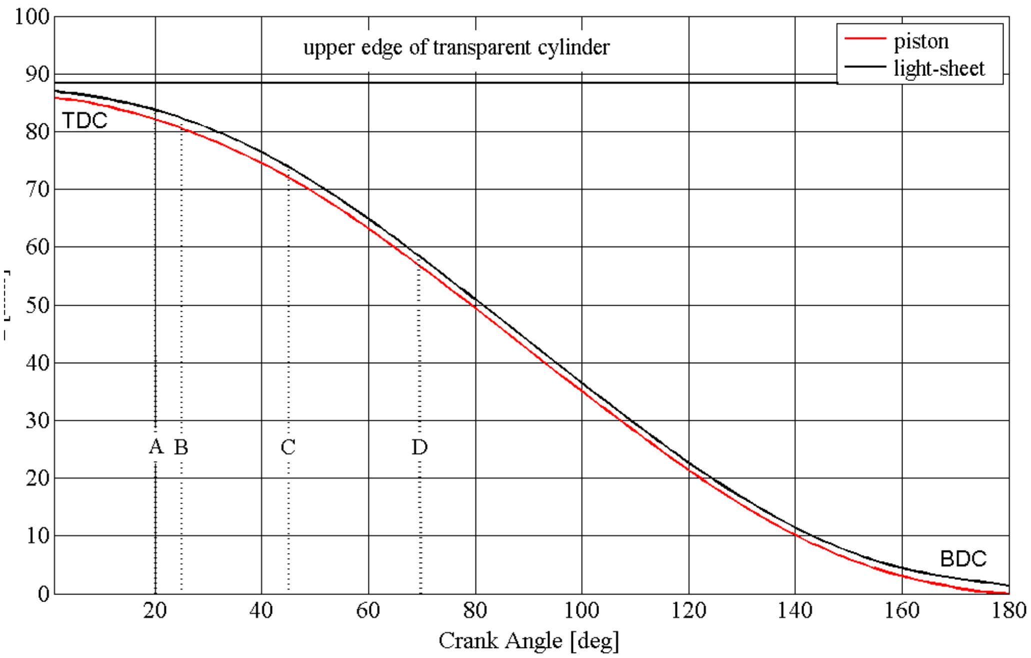

Figure 5. b) measurements of the position of the light-sheet during the downwards motion cycle of the piston in the intake phase; the red line marks the upper edge of the piston and the black line the light-sheet position. For later discussion different characteristic crank angles (A = 20°, B = 26.5°, C = 45.7°, D = 71.5°) are marked in the diagram.

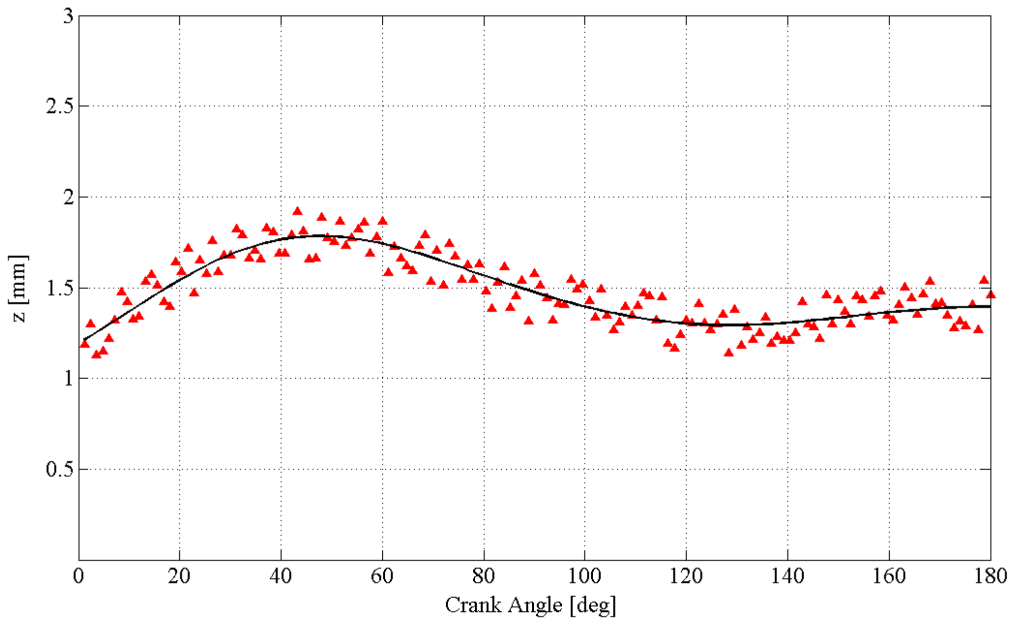

Figure 6. Detailed view of the jitter between the light-sheet and the piston crown during the intake phase.

3. Results

All further results are shown in the arrangement of the valves as illustrated in figure 7 for the bottom view and the side view. Before discussing the flow in the radial plane next to the piston a short characterization of the tumble flow is given in figure 8. The engine conditions (BMW Prince 2) under investigations are set for the generation of a strong tumble flow as seen in the flow visualization on the left. The image is generated from TR-PIV recordings where successive images are overlaid to generate multi-exposure like pictures. The light-sheet position was set in the vertical cross-section aligned with the symmetry plane. A further close-up view is taken with the same camera but a lens with much larger magnification (M=0.5) in the same phase of the intake (magnified window in figure 8). For reference, a red line is drawn within the picture figure 8 right to highlight the position of the light-sheet plane. The magnified tracer let recognize changes of the curvature of the particle paths at the location where the red line is drawn. This indicates that the light-sheet is at the edge of the boundary layer where wall-normal velocity gradients start to increase towards the piston wall.

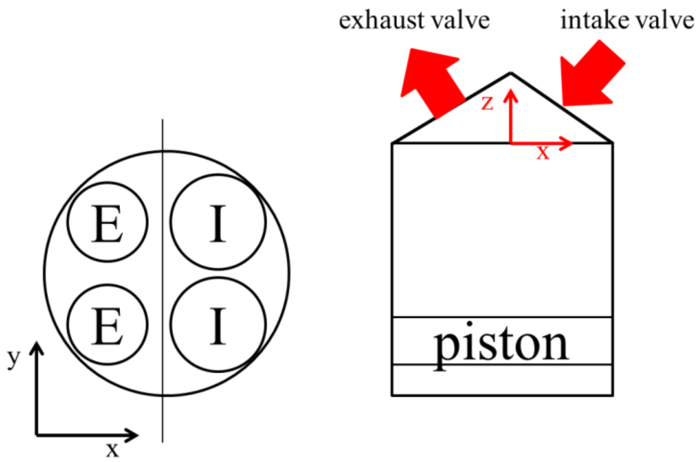

Figure 7. Scheme is representative for all results with position of the inlet (I) and exhaust (E) valves in the background of the images within the radial plane illuminated by the light-sheet.

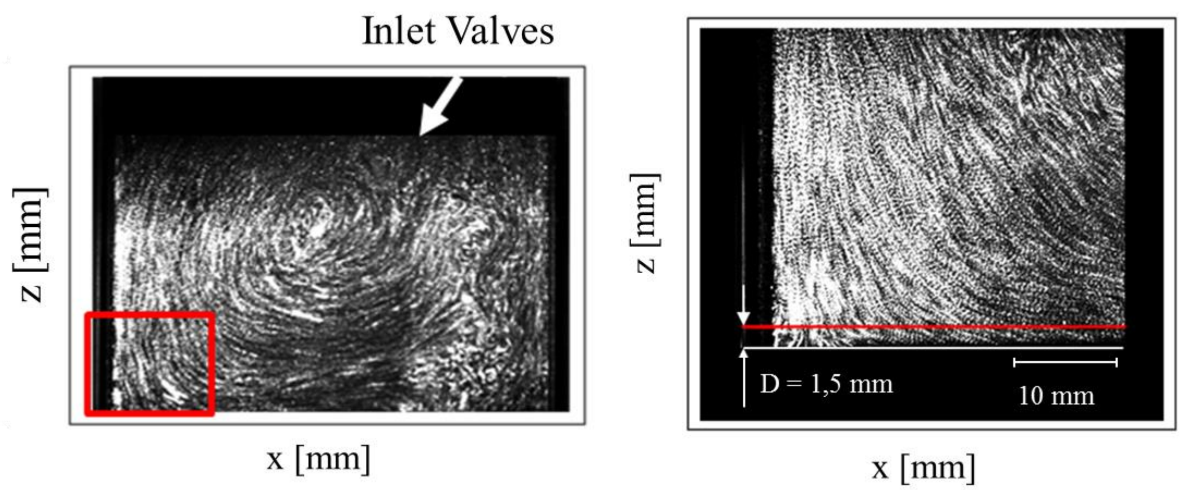

Figure 8. In plane tumble flow generated by the IC engine at CA=80°. In the left upper corner are the exhaust valves, on the right-hand side the inlet valves. Closer look in fig. b) of the near-wall region in the red window marked on the left. The red line with the offset D=1.5 mm highlights the position of the radial light-sheet in the boundary layer.

These recordings were analyzed first to select finally the offset of the radial light-sheet at 1.5mm wall-normal distance; there the measurements characterize the radial flow topology at the outer edge of the boundary layer. Closer to the wall it would be difficult to generate a wall-parallel light-sheet without having large reflections.
The intake stroke is characterized by the opening of the intake valves and the moving piston. Flow is entering from the valves and jets are generated that interact with the piston wall. Figure 9 shows the sectional streamline patterns near the piston wall, which allows the jets' footprints to be recognized. One can recognize a rather symmetric flow arrangement mirrored with the symmetry plane. Several saddle points, characteristic flow dividing separation lines and stagnation lines are well seen. A prominent feature is the formation of two spiraling-out foci next to the center of the disc-like surface of the piston, corresponding to the region of the spark plug above. These vortices of high rotation rate are moving towards the cylinder wall in direction of the inlet valve side and increase in strength. At the same time, two other vortices have grown on each side of the symmetry plane, both originating from regions close to the cylinder wall.

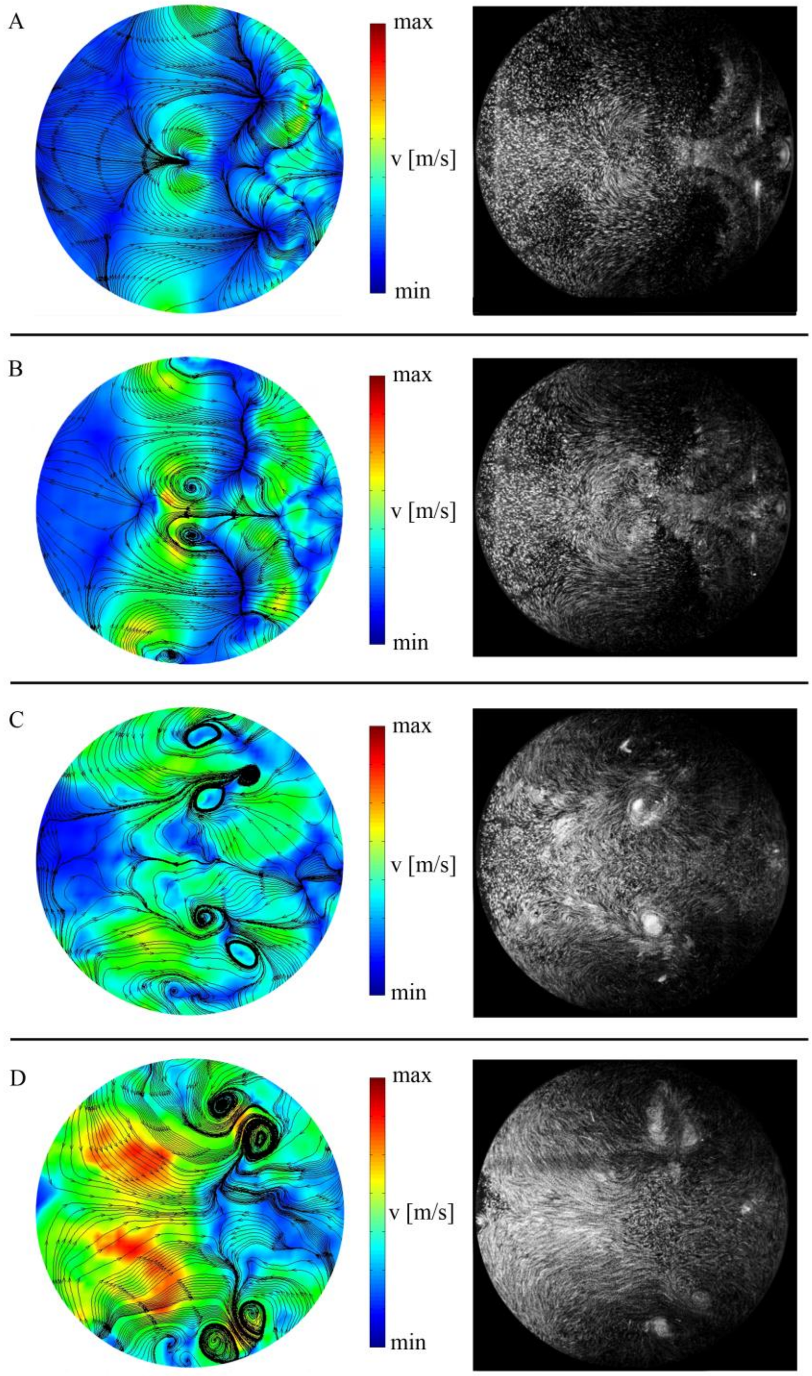

Figure 9. Left: velocity magnitude (color coded) overlaid with sectional streamline patterns. Right: corresponding particle-pathline visualization generated from the same image-sequences by superposition.

One of the near-wall vortices merges with the approaching center vortex, both are of the same sense of rotation. Together with the other near-wall vortex they form a pair of counter-rotating vortices that turn towards the cylinder wall and rest there for longer times.

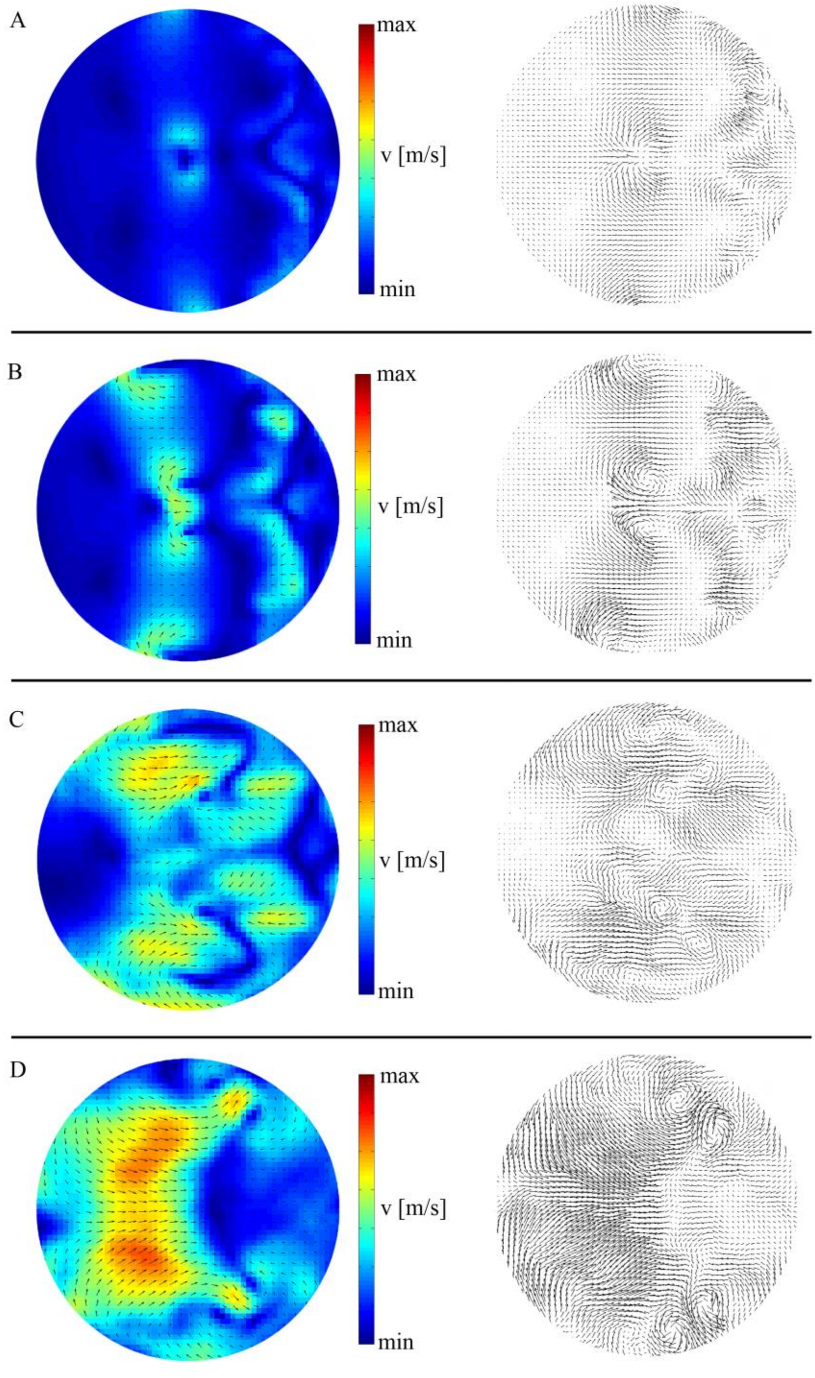

Figure 10. Left: evolution of the phase-averaged velocity field for Crank Angle A, B, C, D, see figure 5 (averaged over 50 cycles, color represents the velocity magnitude); corresponding instantaneous vector fields at the same CA.

A direct comparison of instantaneous 2D planar velocity fields in one single cycle and the velocity fields phase-averaged over the same CA of a total of 50 repetitions of the experiment is given in figure 10. In the instantaneous flow fields there are small scale vortex structures with typical characteristic length scales of approx. 1/20 of the bore. These structures are averaged-out in the phase-average except the stronger vortices that are described above. The blue regions on the piston wall indicate regions of weak transport where the particle residence times near the wall are in order of half the cycle period. These areas are the left and right hand side edge of the piston. For better visualization of the behavior of the larger vortices we calculated the Q-criterion of the phase-averaged measurements and compared those with regions of high RMS-values of the in-plane velocity fluctuations, see figure 11.

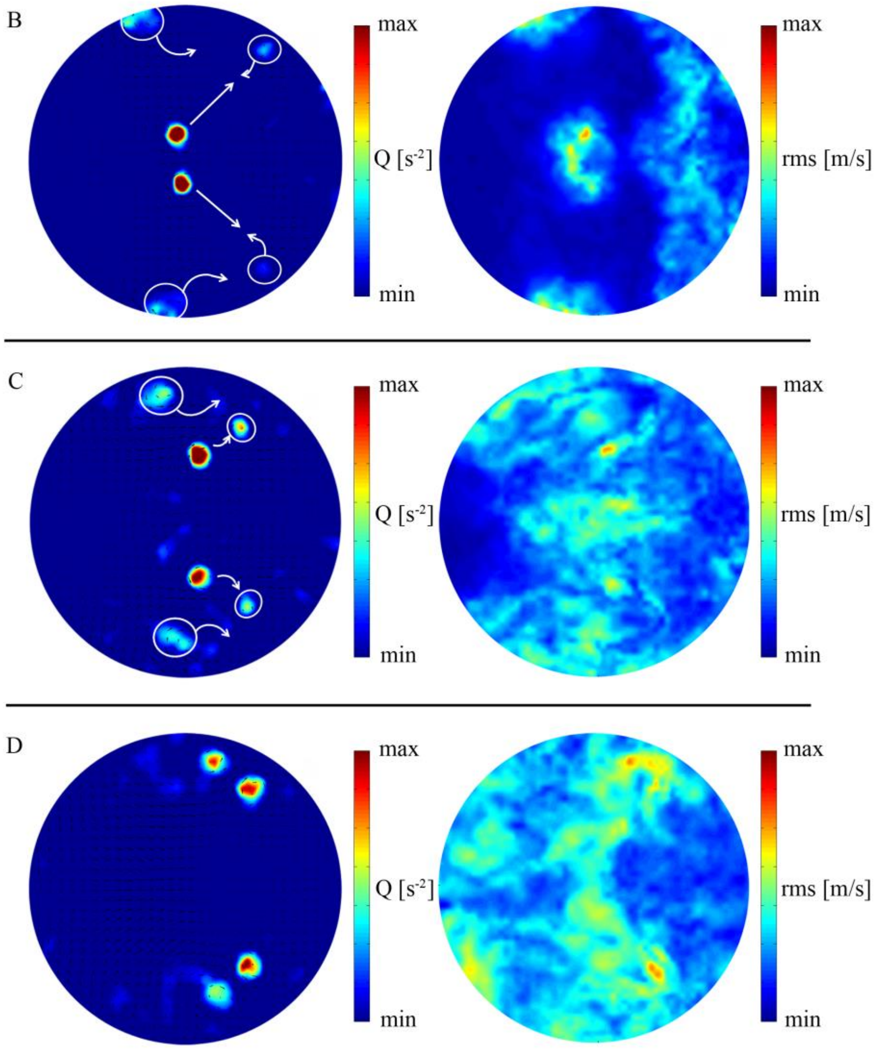

Figure 11. Left: contour plot of high-vorticity regions using the Q-criterion based on the phase-averaged data; right: RMS-values calculated from 50 cycles (results are given at crank-angle postion B, C, D).

The Q-criterion shows the above described movement of the larger vortices from the center towards direction of the inlet side. At Fig 11B (CA=26.5°) one can see the three larger vortices on each side of the symmetry plane. These locations correspond also to regions of higher RMS-values as a consequence of cycle-to-cycle variations of position and size of these structures. The white arrows indicate the motion of the vortices during the intake phase. Note that also other regions on the piston wall evolve where high RMS-fluctuations are seen.

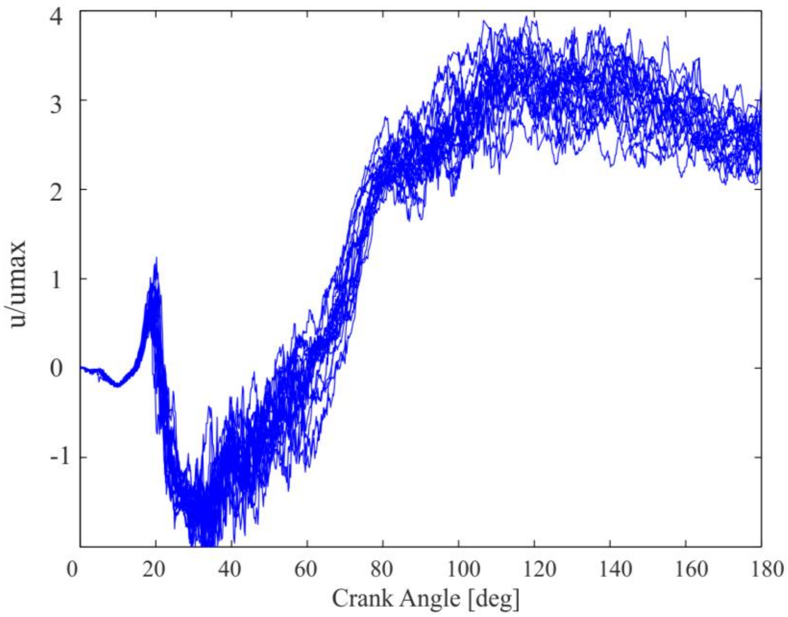

Figure 3. Normalized velocity of 50 cycles during the intake phase.

These regions correspond in the early phase A, B with the stagnation streamline, where flow is separating from the wall in the right-hand side of the piston. Later at phase C, D, the footprint of the tumble flow is seen by the large coherent motion from left to right in the left part of the piston (Fig 10D). The tumble-generated wash-out flow hits the stagnant fluid near the mid of the piston and gives reason for higher RMS-values due to cycle-to-cycle variations within this region (Fig 11D). Another illustration of the cycle-to-cycle variations is shown in the diagram in figure 12. It shows the profiles of the velocity magnitude of the wall-parallel velocity vector in the center of the piston, overlaid for 50 independent cycles. All data are normalized with the maximum piston speed umax. It is well seen that the cycle-to-cycle fluctuations already start in the early intake phase and persist until the end of the intake. This is an important results of the study and hints on the persisting influence of the vortical structures that are being generated in the early intake phase at the valves.

4. Discussion/ Conclusions

The developed flying PIV method using a scanning light-sheet technique allowed us to investigate the temporal evolution of the near-wall flow topology along the piston wall in a 4-valve IC engine flow. The method allows different types of investigations to carry out, one of it is the recording of the flow close to the piston wall over the complete intake cycle. By programming the temporal pulse, it is possible to provide several pulses to a specific point.The system has been tested in a water analogue of a 4-valve BMW engine for the intake phase. The scanning light-sheet follows the harmonic motion of the piston with a constant axial distance of 1.5 mm from the plane piston surface and the flow is recorded with a compact high-speed camera mounted below the transparent piston in the piston shaft. Special interest is the interaction of the tumble flow with the piston wall and the localization of regions of weak wash-out, long residence time as well as high wall-shear. Experiments were run in repeated realizations where fluid is always started from rest. The results of the flow evolution near the piston crown show that intense vortex-structures exist there which play an important role on the near-wall flow topology and which influence the flow structure near the wall. These recorded vortices are understood as the footprints or legs of the vortices generated in the wake of the valves, compare

Abdelfattah (1998) [9]. Because of the downwards motion of the piston, the legs attached to the piston wall are stretched and therefore increase in strength during the intake phase as observed in the experiments. The comparison of a total of 50 intake cycles shows that the motion paths of these vortices along the piston crown vary in time and give reason for cycle-to-cycle variations even if the flow is still at weak turbulence levels. In addition, regions of topologically characteristic stagnation lines in the sectional streamline patterns correspond also to regions of high RMS-fluctuations. These regions are where the tumble-induced wash-out flow propagates with its front into the rather stagnant flow near the piston wall.

It is the first time that TR-PIV results of the flow evolution near the piston crown are measured in detail in one cycle thanks to the developed technique. The high scanning- and frame-rate of order of 1000 sheets/sec in combination with the advantage of a water analogue allowed us to record the flow evolution in a resolution of about 5 frames/CA. On the other hand, the water analogue can only be used for the intake phase and for a single-stroke experiment where the flow is started from rest. These conditions limit the interpretation of the results regarding the mixing of hot and cold fluid within a real IC engine during the intake phase. In addition, the water measurements were limited in equivalent engine speed to a maximum of about 1500 rpm due to the risk of cavitation flow near the valves. Furthermore some specific variations in valve timings require that the fluid is compressible and can therefore not be tested in the water analogue. In principle the technique can be extended to higher speeds and therefore to applications in air-driven transparent IC engines. However, the limiting factor was up to now the frame-rate of the compact high-speed camera mounted below the piston while the scanning device can increase the scanning rate up to 20000 scans/sec. We therefore expect that the technological progress in compact high-speed cameras will allow the adaptation of the developed technique to the complete cycle in an air-driven engine, where the compression phase is also relevant. The special timing of the laser triggering allows also to move the light-sheet down and up as it is required to capture the whole cycle. Moreover, it is also in principle possible to implement more complex motion patterns than the harmonic non-linear motion of the piston if other applications of moving objects are being considered.

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