COMPARISON OF PIV AND LDA MEASUREMENTS WITHIN THE CYLINDER OF A FOUR-VALVE COMBUSTION ENGINE

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Abstract

The flow within a one-cylinder four-valve combustion engine is measured via cycle resolved 2C/2D particle-image velocimetry (PIV) and laser Doppler anemometry (LDA). The velocity field is recorded in eight measurement planes within the cylinder for several of crank angles during the intake and compression phase by PIV. Furthermore, LDA measurements are performed at four different points within the cylinder during the intake and compression phase. The results include a short description of the basic characteristics of the complete in-cylinder flow field and a detailed analysis of the temporal evolution of the flow in the measurement points. The comparison of the findings of the two measurement techniques shows that planar PIV measurements are capable of analyzing the spatial structure of the flow field whereas LDA measurements have a better temporal resolution, i.e., provide a detailed analysis of the temporal development of the flow in single measurement points. Thus, the LDA measurements can be used to identify crank angles where more detailed PIV measurements will lead to a better understanding of the complete in-cylinder flow field.

1 Introduction

The reduction of nitrogen oxide ($\text{NO}_x$), carbon dioxide ($\text{CO}_2$), and soot as well as the reduction of fuel consumption plays an important role in today’s engine development. The flow structures during the intake and compression phase within the cylinder of a piston engine significantly influence the mixing and hence the combustion process (Heywood, 1988). To gain a better understanding of this mixing process, it is inevitable to analyze the temporal and spatial development of the flow phenomena. Particle-image velocimetry (PIV) is a powerful tool to measure planar flow fields with high spatial and temporal resolution (Raffel et al., 2007). However, laser Doppler anemometry (LDA), i.e., a single-point measurement, is capable of generating more detailed turbulence data (Farrell, 2007) and an improved temporal resolution. This article contains measurement results of both measurement techniques and clearly shows the advantages and disadvantages of both techniques as to the resolution of the flow structure within the cylinder of a piston engine.

2 Experimental setup

Optical engine

The four-valve piston engine is based on a Suzuki DR750 motorcycle four-stroke single-cylinder engine and is driven by an electrical 55 kW engine (figure 1). The engine has a bore of 105 mm and a stroke of 84 mm. To accomplish full optical access, the cylinder of the Suzuki engine was replaced by a transparent liner made of plexiglass, which is placed between the original cylinder head of pent roof geometry and an extended lower iron liner, which keeps the extended piston properly aligned. The piston rings are located in the iron liner section. The clearance between the piston and the optical liner is 0.16 mm, which is sufficient to ensure a free piston movement within the optical liner. The resulting larger top-land crevice volume implies a reduction in the effective compression ratio from 9.5 to 9. The engine is operated at 1500 rpm without fuel injection and combustion. Note that the engine is operated only for a duration of a few minutes such that the temperature increase of the Perspex cylinder does not reach critical values. Software programmable digital counter / timer devices and a shaft encoder with a resolution of 1° crank angle are used to...
measure the engine speed, to trigger the laser and the camera of the PIV system, and to measure the corresponding crank angles for the LDA bursts. Two flaps located in front of the intake ports of the cylinder head allow fast switching between unseeded and seeded air. To minimize particle contamination of the optical liner during the engine start process, the flaps are released a few cycles before the data acquisition starts.

**Particle-image velocimetry system**

A schematic of the experimental setup of the PIV system is shown in figure 2. The PIV system consists of a Spotlight 600 Laser, a PCO Sensiscam qe double shutter PIV camera, and a Nikon lens with a focal length of 50 mm and a minimum f-number of 1.8. The maximum laser energy is 400 mJ per double pulse and the maximum frequency is 10 Hz. The light sheet, which is generated by a system of 4 lenses, possesses a thickness of approximately 1 mm and covers the complete cylinder stroke. Reflections due to the plexiglass cylinder are reduced by coloring the backward inner surface. The PCO Sensiscam qe has a resolution of 1376 × 1040 pixels at a frame rate of 4 Hz. Depending on the crank angle, the frame size is reduced. For a crank angle of 180° after top dead center (atdc), the camera is used in full frame mode. Hence, every fourth intake stroke is measured for an engine speed of 1500 rpm. DEHS (Di-Ethyl-Hexyl-Sebacat) with a mean diameter of 0.5 µm is used to generate tracer particles. The positions of the measurement planes are shown in figure 4. The flow in the measurement plane y=00 is recorded for crank angles between 40° and 320° atdc in steps of 20° crank angle. The flow within the remaining measurement planes is recorded for 80°, 160°, and 240° atdc. To yield ensemble-averaged data, about 280 double images were recorded for each measurement plane and crank angle.

**Laser Doppler anemometry system**

The experimental setup for the LDA measurements is shown in figure 3. A commercial LDA system (ILA GmbH, Germany) consisting of a fp50f LDA probe, a LDA controller, and a computer with a high speed analog input card is used. The fp50f LDA probe includes a 75 mW constant wave Nd:YAG laser with a wave length of 532 nm, a bragg cell with a shift frequency of 40 MHz to detect the direction of the velocity, and the transmitting and receiving optics. The beam distance is 45 mm and the focal length is 400 mm. The measurement volume has a diameter of 0.283 mm, a length of 5.026 mm, and contains 59 fringes. The fringe distance is 4.736 µm allowing velocity measurements of ±189 m/s. The backscattered optical signal is sent to the LDA controller using an optical fibre. The LDA controller consists of a photo multiplier, a down shift module, and an analog low and high pass filter. The electrical signal is routed to the computer which uses FFT algorithms and different digital filters for real time data evaluation. The PIV measurements were used to estimate the velocity range at the measurement points to select the down shift and the filter frequencies. By applying down shift, i.e., reduction of the shift frequency, the velocity range decreases. However, down shift is used to apply filters to optimize the LDA system and thus to increase the data rate. As for the PIV measurements DEHS (Di-Ethyl-Hexyl-Sebacat) with a mean diameter of 0.5 µm is used as tracer particles. LDA measurements of the axial velocity component were performed at two different points (A and B) within the cylinder, see figure 4. Two more measurement points (C and D) have been performed by Konrath (2003) using a similar LDA system (ILA GmbH, Germany). The contamination of the plexiglass cylinder by DEHS limited the data rate and the measurement time. Thus, multiple runs per measurement point were performed to obtain a sufficient number of bursts for each measurement point.

**3 Data processing**

**Particle-image velocimetry**

The post processing of the recorded PIV images is done using the commercial software VidPIV by ILA
The ensemble-averaged mean velocity component $u$ is defined by Heywood (1988) and Tennekes and Lumley (1972)

$$\overline{u} = \frac{1}{n} \sum_{i=1}^{n} u_i,$$  \hspace{1cm} (1)

where $u$ represents the velocity and $n$ is the number of the velocity data for the specified crank angle (PIV) or crank angle range (LDA). The ensemble-averaged variance $u'^2$ is defined by

$$\overline{u'^2} = \frac{1}{n} \sum_{i=1}^{n} u'^2 = \frac{1}{n} \sum_{i=1}^{n} (u_i - \overline{u})^2,$$  \hspace{1cm} (2)

with $u'$ as the velocity fluctuation (Heywood, 1988; Tennekes and Lumley, 1972). For internal combustion engines, turbulence plays an important role as it accelerates the propagation of the flame front. For the discussion of the results the turbulent kinetic energy

$$k = \frac{1}{2}(u'^2 + v'^2 + w'^2)$$  \hspace{1cm} (3)

is calculated. Note that depending on the orientation of the measurement plane, $u'^2$, $v'^2$, or $w'^2$ is zero for 2C/2D-PIV Measurements.

### 4 Results

The results of the planar PIV measurements clearly show the three-dimensional character of the complete flow field by composing the single measurement planes into three-dimensional illustrations at 80°, 160°, and 240° atdc as illustrated in figure 5. The figures evidence the in-plane velocity vectors (black arrows) with only every 4th measured vector shown for clarity. Furthermore, the instantaneous streamlines (red lines) and the contours of the turbulent kinetic energy (color code) are visualized. To highlight large vortical structures, the vortex centers within the measurement planes which seem to be part of a single structure, are connected by a black line. For a better illustration and to keep the focus onto the main flow details, only a few measurement planes are depicted. Furthermore, only one half of the engine flow field is shown since it is nearly symmetric to the $y = 0 \text{mm}$ plane.

The vector fields confirm the flow within the cylinder to possess a highly three-dimensional character. At a crank angle of 80° atdc (figure 5(a)), large vortical structures including the dominant ring vortices beneath the inlet valves can be observed. Furthermore, a first impression of the temporal development of these structures can be seen, e.g., the ring vortex is still visible in figure 5(b) at 160° atdc. However, at 240° atdc these structures can not be clearly identified anymore due to a lack of temporal resolution. A more detailed analysis of the three-dimensional character of the flow field is given by Dannemann et al. (2009).

The results of the LDA measurements in the four measurement points are given in figure 6. The solid lines show the mean velocities (left figures) and the variance (right figures) of the phase averaged LDA data at a width of 10°. The dashed lines and symbols represent the results for the corresponding points which were extracted from the vector fields of the PIV data. As measurement points A and B exist in two PIV measurement planes, two sets of PIV data are available for these points. PIV data extracted from the $y = 0 \text{mm}$ plane is denoted by a dashed line since the plane was measured in steps of 20°. PIV data extracted from other planes is plotted by a square or a triangle. The LDA points C and D are only existent in

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**Definitions**

The ensemble-averaged mean velocity component in $x$-direction $\overline{u}$ is defined by Heywood (1988) and Tennekes and Lumley (1972)

$$\overline{u} = \frac{1}{n} \sum_{i=1}^{n} u_i,$$  \hspace{1cm} (1)

where $u$ represents the velocity and $n$ is the number of the velocity data for the specified crank angle (PIV) or crank angle range (LDA). The ensemble-averaged variance $u'^2$ is defined by

$$\overline{u'^2} = \frac{1}{n} \sum_{i=1}^{n} u'^2 = \frac{1}{n} \sum_{i=1}^{n} (u_i - \overline{u})^2$$  \hspace{1cm} (2)

with $u'$ as the velocity fluctuation (Heywood, 1988; Tennekes and Lumley, 1972). For internal combustion engines, turbulence plays an important role as it accelerates the propagation of the flame front. For the discussion of the results the turbulent kinetic energy

$$k = \frac{1}{2}(u'^2 + v'^2 + w'^2)$$  \hspace{1cm} (3)

is calculated. Note that depending on the orientation of the measurement plane, $u'^2$, $v'^2$, or $w'^2$ is zero for 2C/2D-PIV Measurements.

**Laser Doppler anemometry**

As described in the previous section the evaluation of the LDA data was performed in real time during the measurements. To calculate mean velocities and variance values phase averaging with a width of 10° was performed. Due to the limited data rate, a classification of the velocity variation into cyclic variations and turbulent fluctuations could not be performed.
the $y = 0$ mm plane, thus only one set of PIV data is plotted in figures 6(e) - 6(h).

It can be clearly seen that all measurements in figure 6 are in good agreement. On the one hand, the good agreement of the results of two PIV measurements performed in different measurement planes verifies the quality of the PIV measurements, see figures 6(a) - 6(d). On the other hand, the good agreement of velocity and variance values of PIV and LDA measurements show that even a low data rate is capable to measure the qualitative flow characteristics even at high variance values. Note that all measurements are taken in different engine runs with a sufficient time span in between and therefore are statistically independent. Thus, the amount of 150 vector fields used for the PIV analysis is a sufficient value for a qualitative analysis of the flow structure in the cylinder of a four valve combustion engine.

Concerning the temporal resolution of the mean velocity it can be seen from figure 6 that the temporal progression of the flow in the measurement points was captured by LDA measurements. Figures 6(a), 6(b), and 6(e) - 6(h) depict that the results of the PIV measurements performed in the $y = 0$ mm plane with steps of $20^\circ$ crank angle are in good agreement with the curve progressions of the LDA measurements. Thus, the step size of $20^\circ$ is sufficient to capture the temporal evolution of the mean flow field. In contrast, PIV measurements performed in steps of $80^\circ$, e.g. the $x = 20$ mm or $y = 20$ mm plane, are not capable of resolving the progression of the flow. This can be seen in figure 6(c) where the local minimum of the velocity at approximately $100^\circ$ atdc and the negative velocity gradient between $60^\circ$ and $100^\circ$ are not found by analyzing the flow using PIV data.

The variance values of the LDA measurements show high peaks, especially in the beginning of the intake phase. The PIV measurements do not posses these peaks due to a lack of temporal resolution. For example, figure 6(d) shows a high peak at approximately $75^\circ$ atdc and a steep decay of variance between $75^\circ$ and $90^\circ$ atdc, PIV results are only available at $80^\circ$ and $160^\circ$ atdc and therefore a detailed analysis of the temporal variance development based on PIV data is not possible. Thus, to analyze the velocity variance and hence, the turbulent kinetic energy, the crank angle step size of the PIV measurements has to be reduced in this crank angle regime to analyze the temporal evolution of the flow in the beginning of the intake phase in more detail.

5 Conclusions

PIV and LDA measurements were conducted in several axial planes and several single points, respectively, within the cylinder of a four-valve combustion engine. Mean velocities and variances were calculated and analyzed. The comparison of the different measurement results shows good agreement of the findings
Figure 6: Comparison between PIV and LDA measurements of the mean velocity (left) and variance (right) in four measurement points (A, B, C, and D).
and hence, verifies that mean velocity fields and variances can be obtained from the measurements. The latter ones can be used to calculate and analyze the turbulent kinetic. It is shown that planar PIV measurements are capable of analyzing the spatial structure of the flow field, e.g., the dominant ring vortices beneath the inlet valves, whereas LDA measurements have a better temporal resolution. Thus, LDA is capable of analyzing the development of the flow in single measurement points in more detail. Since the vector fields obtained by PIV measurements confirm the flow within the cylinder to possess a highly three-dimensional character, LDA measurements in single points do not suffice to analyze the spatial character of the complex in-cylinder flow field. However, the results of the LDA measurements can be used to identify crank angle regimes where more detailed PIV measurements, i.e., a better temporal resolution, are needed to gain a better understanding of the complete in-cylinder flow field. Further improvement of the spatial resolution can be obtained by using fully three-dimensional measurement methods like holographic particle-image velocimetry (HPIV) which are capable of analyzing the complete in-cylinder flow field in detail Konrath et al. (2002).

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