THREE DIMENSIONAL FLOW FIELD WITHIN A FOUR-VALVE COMBUSTION ENGINE MEASURED BY PARTICLE-IMAGE VELOCIMETRY

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ABSTRACT: The efficiency of combustion processes within four-valve internal combustion engines is significantly influenced by the flow structures that evolve during the intake and compression phase. Recent research showed that the self ignition of modern CAI (controlled auto ignition) engines highly depends on the stratification of fuel, reticulated exhaust gas (EGR), and fresh air. A detailed understanding of this mixing process is inevitable to assess and improve the combustion efficiency, especially regarding pollutant emission and fuel consumption. Thus, the analysis of the temporal and spatial development of the flow phenomena within the cylinder of an internal combustion engine is required.

In this study the flow field in the cylinder of a motored four-valve combustion engine is investigated using standard particle-image velocimetry in several vertical measurement planes. The measurements focus on the analysis of the basic global characteristics of the in-cylinder flow field. Phase-averaged statistics are visualized for characteristic crank angles during the intake and compression stroke by plotting the results of all measurement planes for a specific crank angle in a single figure. Several velocity based methods were used to visualize and analyze the large scale structures within the cylinder. In combination with the turbulent kinetic energy large and small scale spatial structures of the in-cylinder flow can be analyzed.

1 Introduction

The reduction of nitrogen oxide (NOx), carbon dioxide (CO2), 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 the combustion process [1]. To gain a better understanding of this mixing process, it is necessary 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 [2]. Numerous investigations have been carried out to analyze the flow within the combustion chamber via PIV, e.g. [3] [4] [5] [6]. However, most of the previous investigations considered only one or two different axial or radial planes, such that there is only two-dimensional spatial information of the in-cylinder flow field. In this study, the velocity field is measured in several axial planes at different crank
angles via two-component/two-dimensional (2C/2D) PIV to gain information on the spatial large and small scale structures of the in-cylinder flow. By measuring the flow field in multiple planes at different crank angles, it is possible to analyze the spatial distribution and the temporal development of small and large scale structures in the whole cylinder of a four-valve combustion engine. Hence, the complex three-dimensional flow field within the combustion chamber is resolved and its fundamental structures are visualized and analyzed in detail.

2 Experimental Setup

2.1 Optical Engine

The four-valve research engine is based on a Suzuki DR750 motorcycle four-stroke single-cylinder engine and is driven by an electrical 55kW engine (figure 1). The engine has a bore of $D = 105$ mm and a stroke of 84 mm. To have 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 piston and 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 a mean revolution speed of $1500 \text{ min}^{-1}$ without fuel injection and combustion. To avoid a critical temperature increase of the perspex cylinder due to compression, the engine is only operated a limited time period of less than 120 s per test run. A shaft encoder with a resolution of $1^\circ$ crank angle is used to measure the engine speed and the crank angle. As a full Otto-cycle contains two complete revolutions, e.g., $720^\circ$ crank angle, a reflective sensor scans a coding disk mounted to the camshaft to clearly identify intake, compression, power, and exhaust stroke. To perform PIV measurements, the flow needs to be seeded with small tracer particles. These particles are provided in an additional reservoir connected to the cylinder via the intake port. Two flaps located upstream of the intake ports of the cylinder head allow fast switching between unseeded and seeded air [8].

Fig. 1 Optical single-cylinder engine

Fig. 2 Schematic of the experimental PIV setup
minimize particle contamination of the optical liner during the engine start process the flaps are released a few cycles before the measurement starts.

2.2 Particle-Image Velocimetry System

A schematic of the experimental setup is shown in figure 2. The PIV system consists of a Spitlight 600 Laser, a PCO Sensicam QE double shutter 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 is generated using 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. DEHS (Di-Ethyl-Hexyl-Sebacat) with a mean diameter of 0.5 µm is used for the tracer particles. As mentioned above, the seeded air is stored in an air reservoir the flaps until they are released. The PCO Sensicam QE has a resolution of 1376x1040 pixels at a maximum frame rate of 4 Hz. Depending on the crank angle, i.e., the volume inside the cylinder to be covered, the frame size and the recording frequency are adapted. For instance, at a crank angle of 180° after top dead center (atdc) the camera is used in full frame mode triggered by the crank angle. Hence, every fourth intake stroke is measured for an engine speed of 1500 rpm, i.e., with a recording frequency of 3.125 Hz. A computer and software programmable digital counter / timer device is used to measure the engine speed and the crank angle and to release the seeded air through the flaps upstream of the intake ports. Furthermore, the timer signals are used to trigger the laser and camera of the PIV system to enable crank angle resolved measurements. To yield spatial and temporal information of the flow field different measurement planes have been investigated for a range of crank angles. The positions of the measurement planes are shown in figure 3. The flow in the measurement plane y=00 is recorded at crank angles between 40° and 320° atdc in steps of 20° crank angle. The flow within the remaining measurement planes is recorded at 80°, 160°, and 240° atdc. To yield ensemble averaged data approximately 280 double images were recorded for each measurement plane and crank angle.
2.3 Data Processing

The PIV post-processing of the recorded images is done using the commercial software VidPIV (ILA GmbH, Germany). The evaluation is carried out using adaptive cross correlation techniques with window shifting and deformation. The final vector field resolution is approximately $\Delta x = 1.5$ mm, i.e., $\Delta x/D = 0.014$, for all investigated cases. Since the particle image quality decays during one test run due to contamination of the plexiglass cylinder, only the first 150 vector fields are used for further data processing. This value is high enough to calculate statistically representative mean velocity vector fields [3] and was also found to be high enough to yield stable variance values. The ensemble averaged mean velocity component in the $x$-direction $u$ is defined by [1] [7]

$$
\bar{u} = \frac{1}{n} \sum_{i=1}^{n} u_i,
$$

where $u$ represents the velocity and $n$ the number of vector fields for the specified crank angle. The ensemble averaged variance $\overline{u'^2}$ is defined by [1] [7]

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

with $u'$ being the velocity fluctuation and $\sigma_u$ the standard deviation of $u$. Turbulence can be quantified by the turbulent kinetic energy $k$ [7]

$$
k = \frac{1}{2} (\overline{u'^2} + \overline{v'^2} + \overline{w'^2}).
$$

Note that depending on the orientation of the measurement plane, the corresponding out-of-plane component $\overline{u'^2}$ or $\overline{v'^2}$ is not captured in 2C/2D-PIV measurements. To analyze the large scale flow structures in the combustion chamber, the out-of-plane vorticity $\omega$

$$
\omega = \frac{1}{2} \left( \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right),
$$

is used, where the partial derivatives are obtained by a least square fit of the velocity gradients. Another method to analyze the flow structures with respect to the spatial position is to find the vortex center using a vortex center identification criterion [9]

$$
\Gamma_1 = \frac{1}{s} \sum_{i=1}^{s} \frac{\vec{r} \times \vec{v}}{||\vec{r}|| \ ||\vec{v}||}.
$$

The illustration in figure 4 shows that $s$ is the number of grid points used to calculate $\Gamma_1$, $r$ the radius vector, and $v$ the velocity vector at point $i$. Taking into account the local convection velocity $\vec{v}_m$, the vortex core identification criterion $\Gamma_2$ can be defined [9] as
In contrast to $\Gamma_1$, $\Gamma_2$ is Galilean invariant. Furthermore, the $\lambda_2$-criterion, which is also Galilean invariant, is used to locate vortical structures in the flow fields [10]. The quantity $\lambda_2$ is the second eigenvalue of the symmetric matrix $M$, which contains the 3D velocity gradients [10]. Since only in-plane data are captured in this study the gradients and the velocity component in the out-of-plane direction are not taken into account in the analysis. This results in simplified $\lambda_2$ criterion for the obtained 2C/2D PIV measurements [11]. Negative $\lambda_2$-values represent vortex cores.

**3 Results and Discussion**

Figure 5 shows the mean flow field within the y-z symmetry plane of the cylinder at a crank angle of 80° atdc using the four aforementioned methods for the visualization of rotating flows. The characteristic feature of this flow field is the symmetrical pattern of four vortical structures. All criteria are capable to detect these four vortices. However, the $\lambda_2$ criterion seems to be the less robust tool to identify vortex centers as it is more susceptible to the velocity gradients than the others. For instance, the vortex at $y \approx 10$ mm and $z \approx 75$ mm is not clearly detected by $\lambda_2$ in figure 5(c). Furthermore, $\lambda_2$ does not give information on the direction of the vortex rotation. Hence, as far as this study is concerned, the other criteria are better suited to determine flow structures extending over several measurement planes. Focusing on the three criteria $\Gamma_1$, $\Gamma_2$, and $\omega$, it can be seen that the $\Gamma_1$ criterion does clearly identify the
vortex cores whereas the other two criteria, $\Gamma_2$ and $\omega$, are more capable to identify the direction of rotation and intensity such that they can be used to characterize the size of the vortical structure. To visualize the three-dimensional character of the flow field, the $\Gamma_1$ criterion is used in this study. By connecting identified vortex centers that belong to one vortical structure, the three-dimensional character of the flow field becomes more evident.

Figure 6 shows an exemplary instantaneous vector field for the y-z symmetry measurement plane at 80° crank angle using the four different criteria to identify small scale structures. The figure clearly depicts the correlation of the turbulent kinetic energy and the small scale structures. As already shown in figure 5, the $\Gamma_1$ criteria is capable of identifying vortex centers, see figure 6(b) whereas $\omega$ and $\lambda_2$ are most suitable for the visualization of the intensity of the vortical structures. The increased values of $\Gamma_1$ and $\lambda_2$ in the left and right bottom corner of the flow field correspond to the large scale vortical structures that can be clearly seen in figure 5. Figure 6(a) also evidences that the contour plot of the turbulent kinetic energy $k$ correlates with the appearance and intensity of small scale structures. Hence, this quantity will be used to visualize the three-dimensional character of small scale structures in figure 7.

To illustrate the three-dimensional character of the flow field multiple measurement planes for crank angles of 80°, 160°, and 240° atdc are shown in a single three dimensional diagram in figure 7. As the in-plane flow indicates in figures 5 and 6, the structures are almost symmetrical with respect to the centerline ($y=0\text{mm}$) of the measurement field. Thus, only one half of the flow field is plotted. For a better illustration only selected measurement planes are visualized. Figure 7(a) displays the flow field.

Fig. 6 Four criteria ($k$, $\Gamma_1$, $\lambda_2$ and $\omega$) of the mean velocity field to identify small scale vortical structures
THREE DIMENSIONAL FLOW FIELD WITHIN A FOUR-VALVE COMBUSTION ENGINE MEASURED BY PARTICLE-IMAGE VELOCIMETRY

for a crank angle of 80° atdc. Three large vortical structures can be identified: a small c-shape vortex that is shown in the top left corner of figure 7(a), the tumble vortex which is visible in the right part of figure 7(a), and a pair of two large ring vortices that fill the complete cylinder. Note that only one ring vortex is plotted since only one half of the flow field is plotted due to the symmetric flow field. Figures 7(b) and 7(c) show the three-dimensional diagrams for 160° and 240° crank angle atdc, respectively. Both figures depict a complex flow field with large scale vortical structures. The lateral distance of 20 mm between the measurement planes is not sufficient to identify spatial coherent structures. Only the ring vortex, which was observed in figure 7(a) is still evident in the center of the cylinder in figure 7(b). The outer part of the former ring structure, however, is not observed anymore. Concerning small scale vortical structures, the center of the cylinder, e.g., where the two inlet jets merge, is found to be the region where most of the turbulent kinetic energy is generated at a crank angle of 80° atdc. For an increased crank angle, i.e. 160° atdc, the inlet stroke is still in progress and thus the occurrence of small scale structures is still dominant in the center of the cylinder. However, due to the lower intensity of the inlet jets the level is decreased compared to the early intake phase. Furthermore, the turbulent kinetic energy possesses a smoother distribution at an increasing crank angle, i.e., higher values do not only occur in isolated regions, e.g., the center plane. In the end of the compression phase at 240° atdc, a much smaller overall level of turbulent kinetic energy and a very smooth distribution of turbulent kinetic energy are found within the cylinder.

4 Conclusion and Outlook

Planar PIV measurements were conducted in several axial planes within the cylinder of a four-valve combustion engine. Different quantities to analyze and visualize large and small scale flow structures have been applied to the flow within the y-z symmetry plane of the cylinder at a crank angle of 80° atdc. The results were discussed and the findings were used to visualize the complex flow field within the cylinder of a four-valve combustion engine. The resulting figures confirm the flow within the cylinder to possess a highly three-dimensional character. For a crank angle of 80° atdc, large vortical structures, including the dominant ring vortices beneath the inlet valves, can be observed. Furthermore, the flow fields at 160° and 240° atdc are shown. However, to identify spatial coherent vortical...
structures within the different measurement planes at increased crank angles, e.g., 160° and 240° atdc, the spatial resolution of the measurements needs to be increased. Regarding small scale structures, the measurements revealed that the maximum turbulent kinetic energy and the spatial variance of the turbulent kinetic energy decrease at increasing crank angle. Further investigations will be based on higher spatial resolution to identify coherent structures and an increase in measured crank angles to analyze the temporal development of these flow structures within the whole cylinder. Furthermore, fully three-dimensional measurement methods like holographic particle-image velocimetry (HPIV) [8], which are capable to analyze the complete in-cylinder flow field in detail, will be applied to the flow field of the combustion engine.

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References

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