3-D scanning PIV of the flow within a two-stroke water analogue combustion engine

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Abstract

Goal of this work is to characterize the cylinder scavenging process in a water analogue, backward scavenging, two-stroke internal combustion engine (ICE). The measurements are performed using time resolved 3D scanning particle image velocimetry (3D SPIV). The result is 2C-3D dataset. Stagnation flow is typical for the two-stroke IC engine. It is induced by the transfer and the booster ports, resulting in a complex three dimensional flow. Due to the stagnation flow high frequency fluctuations of the flow direction can occur. In order to maintain the two-stroke IC engine competitive in its different applications it is necessary to obtain a better insight of the three dimensional scavenging process. Therefore, 3D measurement techniques are necessary. Recent developments like tomographic PTV allow the reconstruction of 3D velocity fields (Kitzhofer 2009). However, a plurality of optical accesses is necessary. Furthermore, the long processing time for data evaluation is a disadvantage of this technique. Hence, it is unsuitable for the two-stroke engine, due to a limited optical access. Instead, a single camera set-up combined with a scanning light sheet is used. This method is also suitable to investigate the cycle to cycle fluctuations. As Bown et al. (2007) showed it is possible to calculate the third velocity-component from the velocity fields of the scanned planes, using conservation of mass for incompressible flow. The result is a complete three dimensional velocity field (3D 3C) for every scanning cycle of this procedure. Brücker (1997) demonstrated the working principle on IC engines in specific regions of the combustion chamber. With this time resolved measurement technique it is also possible to investigate fluctuations of the flow direction discovered by Hauke et al. (1998). This phenomenon was called flip-flop. The results of the time averaged measurements can qualitatively be compared with experiments in an external driven engine (Britsch 2010). The time averaged flow measurements show a typical tumble motion. Thereby, the flow leaves the transfer and boost ports upwards to the cylinder head, where it moves in direction of the exhaust port and back down. The time resolved three dimensional flow fields are similar to the time averaged results. However, the clearly structured tumble motion of the averaged results is blurred in the time resolved measurements, due to the fluctuations induced by the stagnation flow.

1 Introduction

Two-stroke internal combustion engines (ICE) have been displaced by four-stroke engines in many applications. Disadvantages like high hydrocarbon (HC) and nitric oxides (NO) emissions have become exclusion criteria. However, due to their high power to weight ratio and lower manufacturing costs they are still applied in some fields. To keep the two-stroke ICEs competitive and to open up new fields of application; like for example a range extender, see Schröder (2009) and Fischer (2009); it is important to understand the complete scavenging process. Earlier investigation with laser Doppler anemometry (LDA) showed strong flow fluctuations due to the stagnation flow induced by the transfer and booster ports, (Hauke et al. 1998). The flow from one transfer port outbalances the flow from the opposed transfer port and the other way round. This phenomenon was called flip-flop. Aim of this work is to investigate this stagnation flow and its influences on the scavenging process. Therefore, it is necessary to reconstruct the 3D-flow. Recent developments show a high grade of diversification, both in 3D-measurement principles, as well as in the resulting measurement techniques (Raffel et al. 2007, Hain et al. 2009, Seeger 2002). Especially three
dimensional particle tracing velocimetry (PTV) and 3D-particle image velocimetry became more and more developed during recent years. This is due to the reduced time required for data analysis by the increase of computational power. However, all of the techniques to determine the three velocity components (3C) in a larger three dimensional measurement volume (3D) require a multi camera set-up. The limited optical access to a two-stroke ICE permits only a single camera set-up.

2 Method

Brücker (1995) used a mirror drum to scan a volume of interest with a single light sheet. The images can be evaluated like normal 2C-2D data. With the volumetric information from the scanning light sheet, the third velocity component can be calculated by the using the conservation of mass for incompressible flow, see Bown et al. (2007). Thus, it is possible to investigate the three dimensional flow inside the two-stroke ICE. Instead of a scanning mirror drum, a polygon mirror with 20 facets is used to create the scanning light sheet.

2.1 Polygon scanner

The illumination is generated by a high speed pulse Nd:Yag-laser and a light sheet optics. After passing the optics each pulse is reflected on one facet of the polygon at a different position. This leads to an angular separation of the light sheets (see Fig. 1).

The angular separation is parallelized by a cylindrical lens. Because the lens also focuses the thickness of the light sheet, a second cylindrical lens is needed, to compensate this effect. The second lens is located between the light sheet optics and the polygon mirror. To adjust the laser light sheet correctly, to the polygon, the optical components are mounted on high precise positioning systems (Fig. 2). In order to position the polygon in time to a defined angular position, the polygon needs to be driven by a stepper motor. The whole process is controlled by TTL trigger signal generated by a processor. Generally two different operating modes of the polygon scanner exist.
In the first case all n planes are scanned once during the passage of each facet, i.e. the laser is pulsed n times, the corresponding second images for PIV are obtained during the passage of the following facet (Fig. 3a). So the volume is completely scanned once every two facets. The separation time between the two corresponding images is influenced by the number of measured planes, the scan width and the frame rate of the camera. This leads to a fixed driving speed of the polygon and a relatively long separation time. In the second mode, the reflection on two sequential facets illuminates one pair of double images (Fig. 3b). The next two facets scan the following plane and so on. Thereby, the time separation $\Delta t$ between each double image can be kept small by working at high rotation speeds of the polygon. The measurements performed by using the second method.

![Fig 3. Different scanning modes of the polygon scanner](image)

The minimum separation time is limited by the maximum revolution speed ($r_{\text{max}}$ in seconds) of the stepper motor and the number of facets.

$$\Delta t = \frac{1}{r_{\text{max}} \cdot n_{\text{fac}}} \quad (1)$$

The stepper motor allowed a maximum of 3600 rpm leading to a minimal separation $\Delta t$ of 0.83 ms. Depending on the number of scanned planes $n_{\text{scan}}$, the total time $t_{\text{scan}}$ needed for a full volume scan is:

$$t_{\text{scan}} = 2 \cdot n_{\text{scan}} \cdot \Delta t \quad (2)$$

Equation 2 shows the trade off between temporal and spatial resolution of the volume. As a compromise, the cylinder was scanned with ten planes. The set-up of the ICE and the positions of the planes are described in the following paragraph.

### 2.2 Two-stroke ICE

A modified commercial two-stroke ICE is used to obtain realistic in cylinder flow results without too many simplifications of its geometry. The engine is a TM-Racing engine with a displacement of 100 cm$^3$. It has a bore diameter of 49.98 mm, a piston stroke of 50.6 mm and is equipped with two transfer, one booster and three exhaust ports. A cut through the model engine can be seen in figure 4. Due to the high velocity and the compressibility of air, another fluid is used for the investigations. Compressibility would not allow calculating the 3rd component by solving the conservation of mass. Thus, water replaces air as a fluid. Reynolds number similarity allows reducing the flow rate significantly. Incompressible flow permits however, only steady state
measurements. Therefore, the piston is fixed at a position between the bottom dead centre and a maximum upward position shortly before the closing point of the transfer and booster ports. The position is measured by a protractor. As reference the upper end position is called 0° before transfer port closing (BTC) and the bottom dead centre is then at 50.06° BTC.

A membrane pump pumps the water from a tank through the crank shaft bearing into the crankcase of the ICE. From here it takes its path through transfer and booster ports into the cylinder. Leaving the cylinder through the exhaust ports, the flow is channelled into a basin in which the ICE is placed. A spill closes the loop from the basin (flow box) into a tank. Figure 5a and figure 5b depicts this set-up.

Further changes of the ICE are a transparent cylinder head, as well as transparent cylinder wall above the exhaust ports. The transparent cylinder head is necessary to provide optical access for the camera, which is positioned over the ICE. Illumination is delivered through the exhaust ports and the transparent cylinder part. Cylindrical lenses are used to spread the light sheet into the combustion chamber. Nevertheless it is still difficult to illuminate the complete cylinder.

2.3 Set-up overview

The last part of the experimental set up consists of the high-speed camera (Photron APX RS) and the lens system. Because the camera is controlled externally, its maximum frame rate is reduced to 1500 fps. To assure, that every scanned light sheet is focussed and with the same magnification a telecentric lens system is used. A sketch of the whole test rig is shown in figure 6. For the experiments the whole fluid circuit was seeded with Vestosint particles with a maximum diameter of 63 microns. In figure 7 the light sheet positions are shown.
3 Data analysis

For data analysis, several steps are needed. After sorting the pictures according to their plane, vector plots were calculated by classical PIV algorithms. The correlation windows have a size of 32x32 pixels and an overlap of 75%. Only two filters were used to eliminate false vectors. First, a range validation in which high velocities are filtered and secondly an average filters. Here vectors are averaged within a 5x5 grid. This was necessary to obtain reliable results for the third component calculation with the conservation of mass. Furthermore, since the PIV results for each plane are not synchronous time averaging over the three volume scans is applied. Solving the conservation of mass is the last step. The main algorithm is similar to the solution of Bown et al. (2007).

First of all each vector position in the 3D volume is indicated by i, j, k for the x-, y-, z-directions. The gradients are calculated by a central difference approximation.

\[
\frac{\partial u}{\partial x}_{i,j,k} = \frac{u_{i+1,j,k} - u_{i-1,j,k}}{2\Delta x}
\]

The same procedure is used for calculating \( \frac{\partial v}{\partial y} \). Conservation of mass gives for \( \frac{\partial w}{\partial z} \):

\[
\frac{\partial w}{\partial z}_{i,j,k} = \frac{u_{i+1,j,k} - u_{i-1,j,k}}{2\Delta x} + \frac{v_{i,j+1,k} - v_{i,j-1,k}}{2\Delta y}
\]

Integration leads to the velocity component w:

\[
w_{i,j,k} = w_{i,j,k-1} + \left( \frac{\partial w}{\partial z}_{i,j,k-1} + \frac{\partial w}{\partial z}_{i,j,k} \right) \Delta z / 2
\]

The calculation starts with the topmost plane at the cylinder head. Here we have the boundary condition \( w=0 \). So the formula for the first plane is reduced to:

\[
w_{i,j,1} = \Delta z \left( \frac{\partial w}{\partial z}_{i,j,1} \right)
\]

With the \( w_{i,j,1} \) it is possible to solve the following planes one after the other with the following...
equation. Hereby the index \( n \) is a consecutive variable for actual point.

\[
w_{i,j,n} = \Delta z_1 \frac{\partial w}{\partial z}|_{i,j,1} + \sum_{z=2}^{n} \Delta z/2 \left( \frac{\partial w}{\partial z}|_{i,j,n-1} + \frac{\partial w}{\partial z}|_{i,j,n+1} \right)
\]  

(7)

The result of these equations is a complete 3D-3C data set.

### 4 Results

To confirm whether the calculation is qualitatively correct, or not, the upward velocity component (\( w \)) was measured with a different method. To this end air was used as a working fluid. Also with the piston fixed in one position, the upward directed velocity component was measured with a Prandtl probe at different points of one plane. Because this is a time averaged method, \( w \) was also calculated with time averaged vector plots. Figure 8 shows the results of two methods. On the left side the air measurements show high positive values (indicated by red and blue colours) in the area of the booster port, located at the upper blue arrow. Closer in direction to the exhaust port (red arrow), the flow is directed downwards. Reynolds number similarity is not fulfilled but qualitatively the global distribution is the same.

![Figure 8. Comparison between air measurements using a Prandtl probe (left) of the z velocity component \( w \) [m/s] and the calculated velocity value [m/s] (right)](image)

The z-component of velocity shows a “tongue formation”. The stronger this tongue is pronounced; the higher is the probability of short circuiting the flow. The calculated plot of the z-component of velocity qualitatively shows the same behavior, which proves the principle of calculating the third velocity component. These velocity plots from one plane already give an indication of the tumble flow, formed in the cylinder. In the following section tumble will be resolved plane by plane and then later on to look at the complex three dimensional time resolved results.

#### 4.1 Plane wise examination of the PIV results

The stagnation flow and the flip-flop can be observed in a small area of the crank shaft angle centred at 12° ± 4° BTC. Before reaching 8° BTC, the flow momentum from the right transfer port outbalances the left all the time. At positions over 16° BTC, the left transfer port outbalances the right one. This can be explained either by production tolerances or by a qualitatively insufficient
inflow to the crankcase.

Figure 9 shows two vector plots from plane four with a piston position of 9.7° BTC. The first plot exhibits a strong asymmetry from the right transfer port. 120 ms later, the asymmetry is reversed. If the vector plot averaged over 100 time steps (Fig. 10) is examined, the flow appears to be symmetric, because averaging filters out the fluctuating structures of the flip-flop. However, the temporal resolution of the measurements is not quite sufficient to resolve the transition from one extreme to the other.

For comparison figure 11 shows a time averaged vector plot with the piston at the bottom dead centre, where the resulting flow is asymmetric with greater flow rate from the left transfer port. The flow is channelled by the wall in direction to the exhaust port; this forms a large vortex in the centre of the cylinder. Thus, a symmetric averaged vector plot can be used as an indication for the
occurrence of flip-flop. The situation for the three planes closer to the cylinder head is similar. With occurring flip-flops, the flow also seems symmetrical (Fig. 12).

The fluid follows the cylinder wall downwards to the exhaust ports. Because the exhaust ports are closed at this height, two vortices are formed, where the fluid is channeled downwards. Figure 13 shows the time averaged vector plot with the piston at the bottom dead centre. The flow still remains asymmetric. Instead of following the wall towards the exhaust port, the fluid flows towards the transfer port with a high flow rate. This indicates a tumble motion formed by the sheer layer of the fluid entering the cylinder.

For measurements with appearing flip-flops, the time resolved vector plots show in the near wall region a similar behavior as the time averaged measurements. The flow leans towards the cylinder wall and heads to the exhaust port, whereas in the middle of the cylinder, the flip-flop can still be

**Fig 12.** Vector statistics and velocity magnitude [m/s] from 100 time steps in plane 7 with occurring flip-flops

**Fig 13.** Vector statistic and velocity magnitude [m/s] of 100 time steps at bottom dead centre in plane 7

**Fig 14.** In plane vector plot and velocity magnitude [m/s] in plane 7 with a time separation of 120 ms
observed (Fig. 14).

4.2 The 3D Flow

The tumble motion mentioned above can be understood better using time averaged 3D results. In figure 15 the tumble motion is shown using iso-contours of the calculated speed in z-direction and the speed in x-direction and streamlines. The non transparent surfaces in yellow and blue indicate a constant speed in x-direction induced by the transfer ports. The transparent blue surface shows the upward directed flow caused by the booster port, whereas the transparent turquoise surface illustrates a downward flow direction towards the piston. In the upper part of the cylinder also an important flow component is present, which for clarity is not depicted on the picture. This flow transfers fluid towards the exhaust port. If these main flow components are put together, they form the typical tumble motion indicated by the red streamlines.

Fig 15. Representation of the time averaged flow forming the tumble motion shown by iso-surfaces and streamlines
An example of the 3C reconstruction of flow velocity on one plane for a single time step can be seen in figure 16 using two different angles of perspective.

Here the main flow direction is from the right transfer port towards the left one and remains almost within this plane. On the contrary, the flow from the left port has a larger velocity magnitude and points upwards towards the cylinder head. In a 2C in plane plot of the velocity the left port would show a much lower velocity than the right one.

![Fig 16. Different perspectives of a single time step of the 3D flow velocity [m/s] including streamlines](image)

One can conjecture that the flip-flop is not only present in x-y planes but also in 3D space. Furthermore the streamlines indicate a flow more complex than the time averages from figure 15 would suggest.

In addition figure 17 shows the calculated third velocity component for one time step. Of course compared with the averaged results it scatters more. This means strong gradients between an upward and a downward directed flow. Here all small structures and flow patterns have an influence on the calculated velocity component. This is due to low spatial resolution in z-direction (the relatively low number of scanned planes in comparison to the number of vectors in x and y direction). Thus small vortices, which are detected in one plane, can not be found in a nearby plane. This influences the calculation of the z velocity component.
5 Summary

This work shows the 3C-3D flow structure for the scavenging process in two-stroke ICE that was measured by using time resolved 3D scanning PIV. The third velocity component was calculated using the conservation of mass, as Bown (2007) showed for μPIV data. A comparison with an alternative measurement technique for the third velocity component proved this method viable for use in large scale flows. However, it should be mentioned that small vortices and flow patterns influence the result of the third velocity component to some extent due to the limited number of planes that could be scanned. Nevertheless it is possible to characterize the full in cylinder flow with good time and spatial resolution. Furthermore, the flip-flop fluctuations described by Hauke et al. (1998) are reproduced to some extent. However, the fluctuations they diagnosed only to occur in planes parallel to the piston. But the present results show that the fluctuations are three dimensional. It is also shown that the flow inside the cylinder is quite complex, even for steady flow. In order to make the two-stroke ICE ready for the hybrid generation a lot of improvements have to be made. It has been shown that scanning PIV together with the calculation of the third velocity component is a tool applicable to improve scavenging in two-stroke engines.
References:


