

Tomographic Particle-Image Velocimetry Analysis of In-Cylinder Flows

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ABSTRACT

New combustion processes require an understanding of the highly three-dimensional flow field to effectively decrease fuel consumption and pollutant emission. Due to the complex spatial character of the flow the knowledge of the development of the flow in an extended volume is necessary. Previous investigations were able to visualize the discrete three-dimensional flow field through multi-plane stereoscopic PIV. In this study, cycle resolved tomographic particle-image velocimetry measurement have been performed to obtain a fully resolved representation of the three-dimensional flow structures at each instant. The analysis is based on the measurements at 80°, 160°, and 240° after top dead center(atdc) such that the velocity distributions at the intake, the end of the intake, and the compression stroke at an engine speed of 1,500 rpm are discussed in detail. The flow fields are analyzed by distributions of the velocity fields, the turbulent kinetic energy (TKE), and the Γ_1 vortex identification function. It is the purpose of these tomographic measurements, which enable the instantaneous resolution of the large scale three-dimensional vortical structures of the in-cylinder flow field during the intake and compression stroke without any discrete multi-plane composition of the spatial flow structure, to confirm the development of the ring vortex, the U-shaped structure of the tumble vortex, and the elliptic trajectory of the inlet vortex core. The three-dimensional resolution of the flow field will be used to show the growth of the turbulent kinetic energy due to the free-shear layers in the valve region and its volumetric distribution caused by the tumble vortex which gives insight into the mixing process during intake and early compression.

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INTRODUCTION

The development process of new internal combustion (IC) engines concentrates on reducing pollutant emissions and fuel consumption and yet increasing the power output of the engine. Especially the so-called Controlled Auto-Ignition (CAI) and the Homogeneous Charge Compression Ignition (HCCI) appear to be promising technologies. Both are characterized by a high homogenization and exhaust gas recirculation (EGR). The former avoids rich combustion such that soot emission decreases, whereas the latter significantly reduces the combustion temperature which significantly reduces NO_x emissions. The lower combustion temperatures are achieved through the high thermal heat capacity of the recirculated exhaust gas. Furthermore, fuel consumption is reduced through dethrottling as well as decreased heat release due to the diluted mixture, which leads to lower peak in-cylinder pressures and a higher ratio of specific heats resulting in enhanced engine efficiency and decreased fuel consumption [1]. Lang et al. [18] reported a maximum fuel reduction of 15% and a reduction of NO_x emissions by up to 90 - 99 %.

Unfortunately, CAI and HCCI are limited in their operation range due to knocking and misfiring (Ma et al. [19], Urushihara [28], Bhawe et al. [6]). These combustion instabilities can not be controlled by

combustion performance measures, e.g., air-fuel ratio measurements such that they have to be chemically and physically suppressed. Stapf et al. [26] state that self-ignition highly depends on the stratification of fuel, EGR, and fresh air. Consequently, the control of the combustion process strongly depends on the thermodynamic conditions of the in-cylinder mixture (Adomeit et al. [2]). These conditions are significantly influenced by the gas flow within the cylinder especially during the intake and compression stroke. Hence, the large and small scale structures within these strokes strongly influence the mixing and as such the combustion process (Heywood [16]) since the point of ignition and the propagation are directly influenced by the flow field. New developments try to control these instabilities through model-based control [3]. These approaches rely on reduced-order models of the underlying combustion process. To generate these models of the flow field a detailed analysis of the temporal and spatial development of the characteristic flow phenomena is essential.

Two-component planar particle-image velocimetry (PIV) (2D/2C) has become a standard tool for the analysis of the flow field inside an IC engine. Stansfield et al. [25] measured the crank angle resolved mean flow in the symmetry plane of a IC engine to calculate tumble ratios. They described the angular momentum around specific axis

in the combustion chamber for different engine speeds and found a significant change of the fundamental flow structure between 2,500 and 3,500 rpm. Dannemann et al. [13] performed planar PIV measurements for several crank angles in an unfired one-cylinder four-valve IC engine. They analyzed the three-dimensional structure of the velocity field based on flow field measurements in eight vertical planes. The quasi three-dimensional flow field was reconstructed from the two-dimensional velocity fields for crank angles of 80°, 160°, and 240° after top dead center (atdc). Furthermore, the propagation of the flow field between crank angles of 40° and 320° atdc in steps of 20° was discussed for both symmetry planes. The authors showed that the flow inside an IC engine possesses a highly three-dimensional character. Furthermore, large vortical structures, e.g., ring vortices beneath the inlet valves and their temporal development could be shown.

Stereoscopic PIV measurements, which are capable of visualizing all three velocity components in one measurement plane (2D/3C), were first performed in an IC engine by Calendini et al. [10]. They recorded 35 double images in the center plane between the inlet and outlet valves for different crank angles at 1,000 rpm. However, the ensemble averaged measurements were not able to visualize large scale structures like ring vortices or the tumble vortex. Bucker et al. [8, 9] performed stereoscopic PIV measurements in a set of planes for several crank angles at 1,500 rpm. They visualized large scale structures and analyzed the temporal development of the mean kinetic energy in two measurement planes. However, the highly three-dimensional structure of the flow requires the application of a three-component volumetric or quasi-volumetric measurement technique to instantaneously capture all three velocity components in the complete cylinder.

Volumetric particle-image velocimetry measurements in IC engines are rarely reported in the literature. Holographic particle-image velocimetry measurements were performed by Chan et al. [11], Coupland et al. [12], and van Overbrüggen et al. [21]. Chan et al. [11] introduced a novel holographic camera to perform holographic measurements in the center of the cylinder at 120 rpm. Their results show the feasibility of holographic PIV for the measurement of in-cylinder flow fields. Coupland et al. [12] conducted complex amplitude correlation analyses coupled with object conjugate reconstruction and show their technique to be able to resolve a three-dimensional field inside a diesel engine. Van Overbrüggen et al. [21] were able to resolve a large part of the flow field at high resolution for 1,500 rpm. However, due to the analog recording on the holographic plate it is difficult to record statistically significant samples.

Tomographic particle-image velocimetry (Tomo-PIV) at IC engines was first introduced by Baum et al. [4]. They recorded the flow field at 8 different crank angles at 800 RPM with a depth of field of 4 mm as well as 5 different crank angles with a depth of field of 8 mm. In brief, the feasibility of Tomo-PIV for the three-dimensional measurement of in-cylinder flow fields was shown.

In this study, up to 45% of the complete three-dimensional velocity field is captured at 80°, 160°, and 240° after top dead center (atdc) by tomographic PIV such that the ensemble averaged velocity

distribution at the intake, the end of the intake, and compression stroke at an engine speed of 1,500 rpm can be thoroughly discussed. Compared to Baum et al. [4] the depth of field is increased by a factor of 15 to 60 mm, whereas the spatial resolution is halved such that the analysis focuses on the spatial distribution of the three-dimensional large scale vortical structures in an extended volume. This leads to an analysis of the complete three-dimensional flow field during the intake and compression strokes without necessity to compose the flow field from a set of two-dimensional parallel planes. In this sense, this paper complements the knowledge of the spatial development of large-scale structures such as the tumble vortex, the ring vortex and the spatial distribution of the turbulent kinetic energy, to better understand the mixing process during intake and early compression.

The article is organized as follows. First, the optical four-valve research engine is described in detail. Then, the tomographic PIV setup as well as the processing procedure are explained. This is followed by a description of the used seeding material. The discussion of the results starts with an error estimation. Subsequently, the three-dimensional volumetric flow fields of the three measurement points are explained in detail.

EXPERIMENTAL SETUP

The research engine is a modified Suzuki DR750 motorcycle four-stroke four-valve single-cylinder IC engine. It is driven by an electrical 55kW engine, i.e., the engine is not fired. The bore of the engine is $D = 105$ mm and the stroke is 85 mm with a resulting cylinder displacement of $V = 728$ cm³. The original cylinder of the Suzuki engine has been replaced by a transparent Perspex liner to achieve optical access to the in-cylinder flow. The optical cylinder is placed between the original cylinder head of pent roof geometry and an elongated lower liner that keeps the piston properly aligned. Free piston movement within the optical liner is ensured by a clearance between piston and liner of 0.16 mm. The larger top-land crevice volume reduces the engine compression ratio from 9.5 to 9. To get an undisturbed view of the flow, the camshaft drive chain was replaced by an elongated camshaft and crankshaft. The flat piston crown also consists of Perspex to ensure optical access. The engine is operated at a mean revolution speed of 1,500 rpm without fuel injection and combustion.

The typical progression of the engine speed n , showing the decay due to compression, since the engine is not equipped with a fly wheel, the piston speed, and the valve lift of the inlet and exhaust valves are plotted in [fig. 1](#). The vertical lines mark the measurement points. The three crank angles, 80°, 160° and 240°, have been chosen to visualize the flow during intake, end of intake, and compression stroke. To avoid a critical temperature of the Perspex liner, the engine can only be operated for about $t < 120$ s. A shaft encoder with a resolution of 1° provides the crank angle and can be used to measure the engine speed. Due to the four-stroke cycle length of 720°, a reflective sensor scans a coding disk mounted to the camshaft to clearly identify intake, compression, power, and exhaust stroke. The seeding particles for PIV measurements are provided through an additional reservoir connected to the cylinder intake port. Two flaps in front of the intake ports of the cylinder head allow a fast switching between seeded and unseeded air to minimize the particle contamination of the optical

liner during the engine start process (Konrath et al. [17]). A few cycles before the PIV images are recorded, the flaps are released to provide seeded air for the measurements.

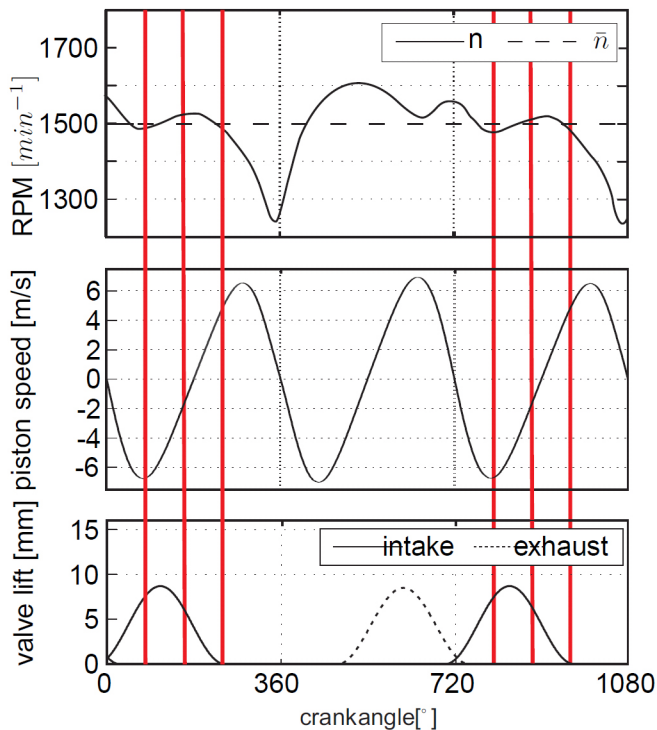


Figure 1. Engine speed, piston speed, and valve lift curves versus crank angle. The vertical lines mark the location of the performed measurements [21].

Tomographic Particle-Image Velocimetry System

The tomographic PIV system consists of two Spitlight 600 single-cavity Nd:YAG lasers with a maximum output power of about 400 mJ per pulse and a wavelength of 532 nm, four sCMOS cameras (PCO edge, 2560 × 2160 pixels, 16-bit, double-frame exposure), and Zeiss lenses with a focal length of 100 mm and f/2.0. The cameras were arranged horizontally on a circular arc around the center axis of the cylinder. This ensures a similar distortion for all four cameras. The angle between camera 1 and camera 4 is $\alpha = 75^\circ$, the angle between camera 2 and camera 3 is $\beta = 36^\circ$ (fig. 2). Scheimpflug adapters, an aperture of f/22, and a magnification of $M_0 = 0.163$ were used, providing a depth-of-field of 64 mm. Due to the radial distortion of the PMMA-cylinder, 17 calibration planes were used to calibrate and match the viewing planes for each camera. The software used for evaluation interpolates linearly between the calibration planes. Therefore, a high amount of calibration planes is necessary to cancel the strong radial distortion produced by the perspex liner. The 17 calibration planes ensure a calibration for the whole volume of the measurement field. The light band was formed by an expanding and collimating lens. A rectangular aperture was used to limit the illuminated volume. The setup leads to a measurement volume with an area of 60 mm × 60 mm and a height depending on the crank angle. Figs. 3 and 4 illustrate the cubic measurement volume at a crank angle $\theta = 160^\circ$ and a horizontal plane of the measurement volume. A programmable timing unit (PTU, LaVision) was used to

obtain 300 phase-locked TPIV images at selected crank angles during intake and compression (fig. 1). Note that a convergence check showed 300 cycles to be sufficient.

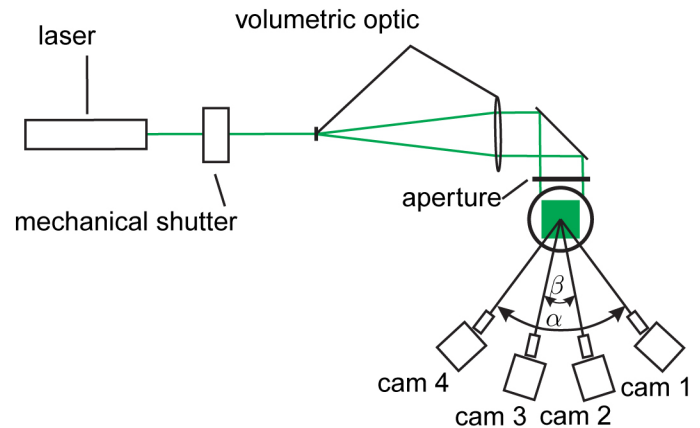


Figure 2. Tomographic PIV setup. Volumetric optic consists of a $f = -25$ mm expanding lens and a $f = 200$ mm collimating lens.

Tomographic Pre-Processing

The commercial software DaVis 8.14 (LaVision) was used to process the raw data. Before the volume reconstruction was performed, reflections at the pent roof and the piston were masked out and a 5×5 sliding minimum was subtracted from the raw images to remove background noise. Additionally, a 3×3 Gaussian smoothing was applied to further improve the image quality. A transformation matrix (3rd order polynomial approach) based on the images of the 17 calibration planes was used to match the viewing planes of all four cameras. Subsequently, several volume self-calibration steps were applied for the different measured crank angles to further reduce the deviation of the 3rd order polynomial approach leading to a remaining deviation of less than 0.2 pixels.

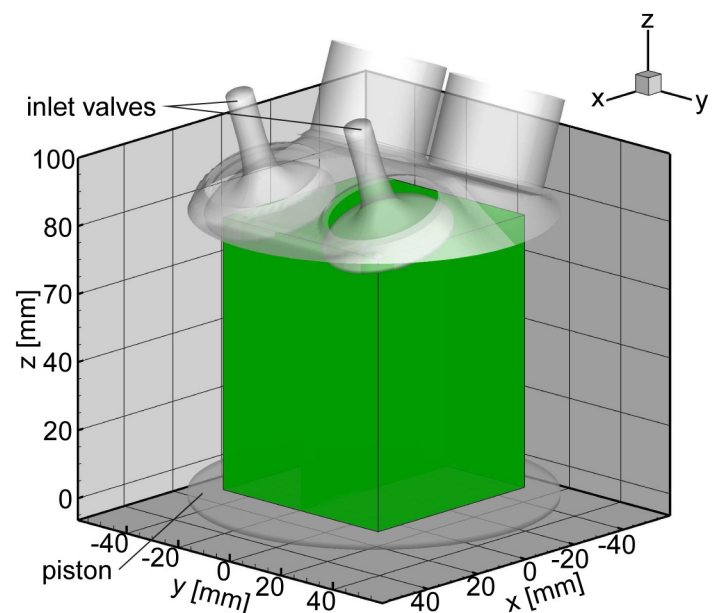


Figure 3. Three-dimensional view of the measurement volume (green).

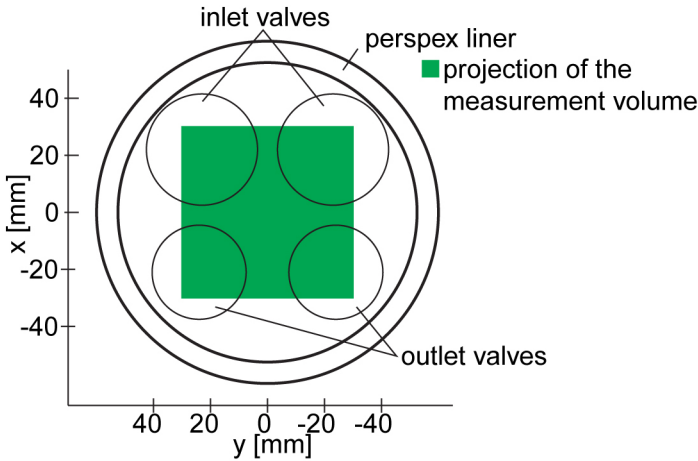


Figure 4. Top view of the measurement volume.

PIV (Post-) Processing

The volumetric reconstruction was performed by an iterative multiplicative algebraic reconstruction technique (fast-MART, Davis 8.14, LaVision) with a maximum particle density of 0.023 particles per pixel (ppp).

For volume reconstruction the algorithm uses 5 iteration steps with smoothing between each step. A multipass direct correlation with decreasing interrogation box size and a final step of $96 \times 96 \times 96$ voxel³ (3.4 mm^3) was used to calculate the velocity fields. The data were determined using 75% overlap which results in a vector spacing of 0.85 mm. A $5 \times 5 \times 5$ vector universal outlier detection was used after each correlation step to detect spurious vectors (Westerweel et al. [30]). The flow field was smoothed by a $3 \times 3 \times 3$ Gaussian smoothing algorithm. In the final step, the same universal outlier detection was used, whereas the smoothing was skipped. The Tomo-PIV post-processing was done using Matlab (The Mathwork Inc.).

The ensemble-averaged velocity, the turbulent kinetic energy (TKE), and the Γ_1 vortex identification function were determined to analyze the velocity fields. The ensemble-averaged mean velocity component in the x-direction $\bar{u}$ (fig. 3) is defined by

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

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

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

with u' being the velocity fluctuation and σ_u the standard deviation of u . Note that the overall velocity fluctuations result from cyclic variations and the turbulent fluctuations. The turbulent kinetic energy (TKE) is computed by

$$k = \frac{1}{2} (\overline{u'^2} + \overline{v'^2} + \overline{w'^2}) \quad . \quad (3)$$

According to Dannemann et al. [13], the TKE possesses an uncertainty range due to the fact that it also includes the cyclic variations. Nevertheless, the qualitative character of the turbulent fluctuations can be described by the TKE.

To visualize the vortical structures, the Γ_1 vortex identification function (Graftieaux et al. [15]) was used. The dimensionless scalar function Γ_1 is defined as follows:

$$\Gamma_1 = \frac{1}{S} \sum_{i=1}^s \frac{\vec{r} \times \vec{v}}{||\vec{r}|| ||\vec{v}||} \quad . \quad (4)$$

Here, s represents the number of grid points to calculate Γ_1 , $\vec{r}$ the radius vector, and $\vec{v}$ the velocity vector at point i . In this work, $S = 3 \times 3$ grid points are used to calculate Γ_1 as explained by Dannemann et al. [13]. Since the Γ_1 vortex identification function can only be applied for 2D flow fields, the flow field has been divided into several discrete planes. For each plane Γ_1 was computed separately and subsequently summarized over the whole volume. In so doing, the Γ_1 vortex identification function could be determined for the whole vector field in all three coordinate directions. Positive values of Γ_1 refer to vortices with a positive mathematical sense of rotation and negative values of Γ_1 to vortices with a negative sense of rotation. Note that Γ_1 is not Galilean invariant. However, it provides a simple and robust way to identify the center of vortical structures.

To calculate the Γ_1 -function for figures 13 and 14 the x-z center plane has been rotated about the z-axis in $\Delta\theta = 5^\circ$ steps. The new in-plane vectors can be calculated by the three-dimensional volume using a rotation matrix and the velocity vectors at the given grid points:

$$\vec{v}(\alpha) = \begin{bmatrix} \cos \alpha & -\sin \alpha & 0 \\ \sin \alpha & \cos \alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} u \\ v \\ w \end{bmatrix} \quad . \quad (5)$$

This enables a three-dimensional visualization of the large-scale vortical structures.

Tracer Particles

Due to too low a light intensity particles with better light scattering behavior than the standard Di-Ethyl-Hexyl-Sebacat (DEHS) droplets with a diameter of $0.5 - 1 \mu\text{m}$ are required. Therefore, Expancel Microspheres (MS) with a mean diameter of about $40 \mu\text{m}$ and a

density of 25 kg/m^3 were used. To ensure that the flow following behavior of the particles is sufficient, the relaxation time τ , described by Ruck et al. [23],

$$\tau = \frac{2}{9} \frac{r^2 \rho_p}{\nu \rho_f} \quad (6)$$

was calculated. The quantity r is the radius of the particle, ρ_p the density of the particle, and ρ_f the density of the fluid. With the values given above, the relaxation time is $\tau = 119.35 \mu\text{s}$, whereas DEHS possesses a relaxation time of about $\tau = 3 \mu\text{s}$. Hence, a Stokes number S_k can be calculated for both particles (Tropea et al. [27])

$$S_k = \frac{u_f \cdot \tau}{l_f} \quad (7)$$

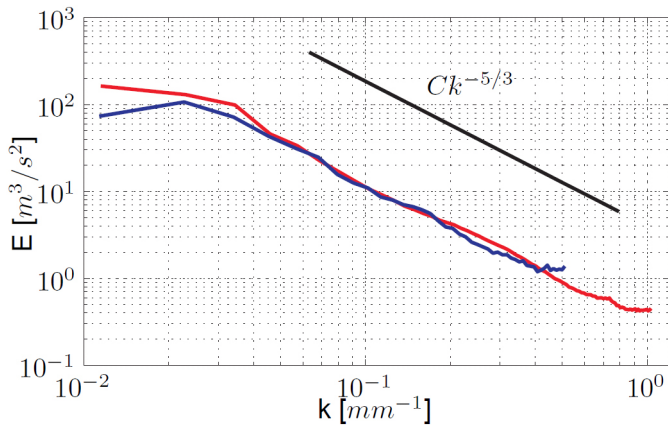


Figure 5. Energy spectra at a crank angle of 160° atdc obtained 2C-PIV measurements with DEHS (red) and MS (blue) [21].

Assuming a maximum flow velocity u_f of about 20 m/s (Dannemann et al. [13]) and an integral length scale l_f of about 3.5 mm (Petersen and Ghandhi [22]), the Stokes number for microspheres (MS) can be calculated to $S_{k,MS} = 0.682$ (Stokes number for DEHS: $S_{k,DEHS} = 0.044$). Tropea et al. [27] state that the condition $S_k \leq 0.1$ yields an acceptable flow tracing accuracy with errors below 1%. That is, the analytical results lead to the assumption that microspheres might not be appropriate for measurements in IC engines. Hence, two component PIV measurements with MS and DEHS were performed to analyze the flow-following behavior in more detail. The measured crank angle was 180° . The resolution was $16 \times 16 \text{ px}$ (1.4 mm^2) with a final interrogation window size of $16 \times 16 \text{ px}$ and an overlap of 50% for Microspheres and $8 \times 8 \text{ px}$ (0.7 mm^2) with an overlap of 50% for DEHS. The velocity fields were used to calculate the energy spectra as explained by Petersen and Ghandhi [22] for both measurements at a given point ($[x,z] = (0 \text{ mm}, 50 \text{ mm})$). Fig. 5 shows that for both particles the spectrum of the inertial sub-range is well captured. Furthermore, both energy spectra show good agreement.

Additionally, fig. 6 shows the ensemble averaged velocity field based on 40 independent snapshots at 160° in the y-z symmetry plane for DEHS (fig. 6a) and MS (fig. 6b). The comparison of both flow fields evidences a high correspondence, i.e., the large scale vortical structures are well captured and coincide. Slight deviations are due to the highly turbulent character of the flow field. These results and measurements performed with microspheres by van Overbrüggen et al. [21] lead to the assumption that MS can be used for tomographic PIV measurements of the large scale structures, i.e., in the range of the integral length scale, of the flow field in an IC engine. For measurements in the range of the Taylor length scale, the flow-following behavior of MS seems to be not appropriate. For this reason it has to be emphasized that structures in this range are not resolved in this study.

ERROR ESTIMATION

To assess the quality of the PIV measurements, the mass conservation principle (Zhang et al. [31]) was applied. The mass conservation equation reads

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_i)}{\partial x_i} = 0 \quad (8)$$

Since in the cold flow field the temporal (fig. 7) and spatial variation at a given crank angle can be assumed negligible, eq. 8 can be simplified to

$$\frac{\partial u_i}{\partial x_i} = 0 \quad (9)$$

At equidistant spacing the divergence of the velocity vector can be approximated by

$$\Delta_G U = \sum_{i=1}^3 \frac{\Delta u_i}{\Delta x_i} \quad (10)$$

to assess mass conservation, i.e., non-zero values of $\Delta_G U$ indicate an uncertainty of the measurement results. The quantities Δu_i and Δx_i denote the discretized velocity gradient and the equidistant vector spacing. Figure 8 shows the probability density function (PDF) of the divergence of the velocity vector at several crank angles. It is evident that the maximum of the PDF at 80° atdc is slightly shifted to positive $\Delta_G U$ values. The broadening of the PDF is due to the higher overall velocity during the intake. The shift for 80° and 160° of the peak value and the widening of the distribution express the fact that the spatial resolution of the measurement cannot sufficiently resolve the high velocity gradients especially in the upper region of the cylinder. The increasing value of the PDF for 160° atdc and 240° atdc shows the decelerating nature of the flow field and therefore a higher PDF value for zero divergence.