3D micro-scale velocimetry methods: A comparison between 3D-µPTV, stereoscopic µPIV and tomographic µPIV

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Abstract In this paper we compare evaluation methods for 3D micro-scale velocimetry. The three methods are stereoscopic micro Particle Image Velocimetry (stereoscopic µPIV), 3D micro Particle Tracking Velocimetry (3D-µPTV) and tomographic micro Particle Image Velocimetry (tomographic µPIV) using a 3D-correlation technique. The raw data for all three methods is recorded with a stereomicroscope. Stereoscopic viewing from two different angles is achieved by the use of a large diameter stereo objective lens with two off-axis beam paths. Additional floating lenses in the beam paths in the microscope body allow a magnification up to 23x. The stereo-PIV images are captured simultaneously by two CCD cameras. The stereoscopic imaging is calibrated by a first rough calibration outside of the microchannel in air. A high-precision calibration grid is translated along the z-direction with a piezo stack. Then the calibration is corrected to the optical conditions inside a closed microchannel by self-calibration on the tracer particle images. Due to the very small confinement, a standard calibration procedure for the stereoscopic imaging by means of a calibration target is not feasible. The different evaluation methods require stereoscopic recording with self-calibration on the particle images, but the requirements on particle image size, seeding density and depth of focus are different and need to be carefully adjusted. As a reference experiment we have chosen the strongly three-dimensional laminar flow in a T-shaped micromixer at moderate Reynolds numbers Re = 100 to 200. We show first results of 3D-µPTV and tomographic µPIV measurements and compare them to stereoscopic µPIV results. The measurements show that the accuracy of all methods is limited by the small viewing angle of the stereomicroscope. The volumetric reconstruction creates particle images that are heavily elongated in the viewing direction, which reduces the accuracy of the tomographic µPIV evaluation.

1. Introduction

While most microfluidic devices have a relatively simple and two-dimensional geometry and the flow is mostly laminar or even creeping, the flow structures evolving in such a microfluidic device can be of complex three-dimensional nature. Typical examples are liquid-liquid flows or gas-liquid flows. In liquid-liquid flows the droplet is used as a reactor of confined volume. In gas-liquid flows the bubble is used to mix the liquid between two successive bubbles. In combination with a meandering channel the liquid flow becomes three-dimensional and mixing is improved (Günther et al., 2005). Also the manipulation of particles by external forces can result in three-dimensional particle trajectories (Megens and Prins, 2005). Recirculation zones created by proper superposition of electro-osmotic flow and pressure driven flow in the opposite direction create well-defined reaction zones with three-dimensional circulating flow. Mixing in microchannels is enhanced by the creation of three-dimensional flow patterns. The staggered herringbone mixer creates three-dimensional flow at Reynolds numbers Re < 10 by asymmetric grooved surfaces (Stroock et al., 2002). Another example is the serpentine mixer, which is operated at high Dean numbers (Jiang et al., 2004). Secondary flow patterns evolve and mixing increases. A T-mixer operated at Re > 100 shows interaction of the two inflows, very strong three-dimensional flow and an increased contact surface of liquids from the two inflows, which improves diffusive mixing (Wong et al., 2004).

The examples mentioned above are among the most efficient applications in microfluidics and they include complex fluid mechanics. We developed a microscopic PIV system (Lindken et al. 2006) for the investigation of three-dimensional flows, which is based on stereomicroscopy as
described in Sect. 2. The raw data can then be evaluated with stereoscopic micro Particle Image Velocimetry (stereoscopic µPIV), 3D micro Particle Tracking Velocimetry (3D-µPTV) or tomographic micro Particle Image Velocimetry (tomographic µPIV) using a 3D-correlation technique. In Sect. 3 the calibration procedure is presented. Sect. 4 describes the raw data and the image preprocessing. The three evaluation techniques and their optimal optical conditions are described in sect. 5 and first results are presented in Sect. 6.

2. Experimental set-up

The stereo µPIV set-up is described in Lindken et al. 2006. The µPIV method as first introduced by Santiago et al. (1998) and developed to its current state by Meinhart et al. (1999) has been applied to stereomicroscopy by using the principles of stereo-PIV (Prasad and Adrian 1993, Prasad 2000). In addition a novel calibration procedure (Wieneke 2005) is used for the integration of Prasad’s stereo-PIV method to a stereomicroscope.

The stereo-µPIV system consists of a stereomicroscope with a filter-set for fluorescence imaging, a double-pulse laser, light-shaping optics, fluorescent tracer particles, two digital cameras in double-frame mode, a programmable timing unit for synchronization of the components and a PC for data acquisition and evaluation. The set-up is shown in Fig. 1.

A stereomicroscope for fluorescence imaging (Leica MZ16 FluoCombi III) is used with a double video adapter and a single stereo objective lens (Leica Planapo 2x or Leica Planapo 1x). While the magnification of the stereo lens is fixed at 1x or 2x, the total magnification of the microscope can be varied from 0.7 times to 11.5 by means of a ‘floating lens’ in the microscope body. The total magnification is the fixed magnification of the stereo lens multiplied with the variable magnification of the lenses in the microscope body. The maximal achievable magnification of the stereo-microscope with lenses that are currently available is 23 times. The two optical beam paths penetrate the same stereo lens at different off-center positions, resulting in a difference in viewing angle. The stereo lenses are corrected for perspective viewing in such a way that the focal planes of the two angular viewing directions are parallel to each other and that there is no perspective distortion. This is in contrast to images recorded when matching the Scheimpflug condition (Prasad 2000). The viewing angle of the stereomicroscope changes with a change of the magnification. A third beam path is used to illuminate the observation area.

A double-pulse Nd:YLF laser (New Wave Pegasus) with a nominal pulse length of 100 ns serves as light source. The light beam is coupled into the third emission beam path of the microscope as shown in Fig 1. Two digital cameras (LaVision Imager Intense) with a high quantum efficiency of 62% at 527 nm are mounted to the double video adapter on the stereomicroscope. The overlap in the direction of the optical axis (here referred to as the z-direction) of the corresponding camera images is carefully adjusted with the help of a calibration target. From test measurements of the calibration target we estimate the mismatch of the depth of focus of the two cameras to within 1.5 µm. A programmable timing unit controls the simultaneous capture of the stereo-µPIV recordings as well as the illumination with the Nd:YLF laser.

As a test experiment the flow in the mixing zone of the microfluidic T-mixer is investigated. The experimental set-up is shown in the lower half of Fig 1. The flow is driven by two pressurized tanks filled with water in order to generate a controlled pulsation-free inflow. The water is seeded with fluorescent polystyrene tracer particles. The particle diameter is chosen according to the evaluation procedure as explained in Sect 4. For the stereo-µPIV experiments we use 570 nm diameter particles, while for the 3D-µPTV and the tomographic µPIV experiments the particle diameter is 1.3 µm. The tracer particles are coated with polyethylene glycol (PEG), which makes the surface of the tracer particles hydrophilic. Adhesion of tracer particles to the walls is significantly reduced with the hydrophilic coating, and we thus reduce the problem of out-of-focus particle images from particles sticking to the wall.
The mass flow rate is kept constant by means of two mass flow controller (Bronkhorst Liquiflow), one for each inlet. In earlier measurements with only one flow controller it was not possible to achieve the same mass flow at both inlets with only one flow controller due to different pressure drops in the inlet ports (Lindken at al., 2005a-c).

For the measurements different T-mixer geometries have been used. Here we present data from a T-mixer with two inlet channels of $300 \, \mu m \times 200 \, \mu m$ cross-section and an outlet channel of $600 \, \mu m \times 200 \, \mu m$ cross-section. The Reynolds number for the $600 \, \mu m \times 200 \, \mu m$ cross section T-mixer is set to $Re = 270$. Stereo-μPIV reference measurements in this geometry will be presented in the oral presentation. The microfluidic set-up has been set under pressure to prevent cavitation. The liquid leaving the T-mixer is collected in a pressurized tank. The pressure in the two feeding tanks was 2 bars, while the pressure in the outlet tank was 1.5 bars.

### 3. Calibration procedure

In large-scale applications one would place a calibration target in the focal plane (or in the lightsheet) to determine the relative position of the two cameras and the focal plane, but this is difficult, if not impossible, inside a closed micrometer-sized channel.

For this reason we developed a different calibration procedure. A rough calibration of the two viewing directions is done outside of the microchannel in air with a high-precision calibration grid translated along the $z$-direction at several positions as shown in Fig. 2. The calibration grid has targets printed on a glass surface with $200 \, \mu m$, $100 \, \mu m$, $50 \, \mu m$ and $20 \, \mu m$ spacing and a nominal accuracy of 20 nm. First the calibration grid is placed in focus with the help of a x,y,z-translation stage. Then the calibration grid is moved along the $z$-direction with the help of a piezo stepper (Piezosystem Jena MIPOS 500 SG). The piezo stepper allows a maximum translation of $500 \, \mu m$ with a nominal reproducibility of 65 nm in closed loop operation mode. We have chosen nine calibration plates with $10 \, \mu m$ distance for the Leica Planapo 1x lens with $60 \, \mu m$ depth of correlation, while for the Leica Planapo 2x lens with $15 \, \mu m$ depth of correlation we have chosen five calibration plates with $5 \, \mu m$ distance. With the piezo stack the positioning error is less than 1.3%.
After the rough calibration the stereo-µPIV images are recorded. Then the computed volume mapping function, which relates the coordinates in the object plane to camera pixel positions, is corrected by a self-calibration method described by Wieneke (2005). The self-calibration method corrects the mapping function towards the actual measurement plane inside the microchannel by first computing a disparity map through ensemble cross-correlation of PIV images recorded simultaneously by camera 1 and camera 2. Then the correction for the position of the measurement plane in space is derived from the disparity vectors by triangulation (determination of the best-fit coordinate in the object plane corresponding to two camera pixel positions of camera 1 and 2), and the mapping function is transformed accordingly taking the change of index of refraction due to the glass-water interfaces into account (Wieneke 2005). Here a multi-plane polynomial function of third-order has been chosen that is more suitable for infinity-corrected microscopes than a camera pinhole model.

Fig. 2 (a) Schematic of the rough calibration procedure in air. (b) Image of the calibration target.

Fig. 3 Schematic of the optical conditions for the experiment. The angle $\alpha_{\text{air}}=7.4^\circ$ changes to $\alpha_{\text{water}}=5.7^\circ$ when passing from air ($n=1.0$) through glass ($n=1.54$) into water ($n=1.33$). In the self-calibration procedure the three-media-model takes into account the air-glass-fluid transitions by means of ray tracing. The dashed lines in the water region ($n=1.33$) indicate the thickness of the depth of focus of the Leica Planapo 2x lens in comparison to the channel depth. The depth of focus for the Leica Planapo 1x lens is four times larger.
4. Raw data and image preprocessing

After the raw data is obtained with the stereomicroscope, the measurements are calibrated and the images are preprocessed to improve the signal to noise ratio as described in Lindken et al. 2006. The individual image preprocessing operations are:

- Compensation for mechanical vibrations during the recording of the individual images through a correlation of image 1 with image n and a shift by the resulting displacement,
- Reduction of the constant background noise from particles that adhere to the walls by subtracting a sliding minimum over time of 11 consecutive images for each individual pixel,
- Reduction of image random noise of particle images by means of image smoothing using a 3x3-pixel low-pass filter,
- Further reduction of background noise by subtraction of a spatial 9x9-pixel sliding minimum on the individual images.

Figure 4 shows the effect of the preprocessing. Figures 4a) and 4c) are recordings of 570 nm tracer particles. The data in Figure 4c) is the data of Figure 4a) after preprocessing. The recordings in Figure 4b) and 4d) are recorded with 1.3 µm tracer particles. The better quality of the raw data (Fig. 4b) is clearly visible. Figure 4d) shows the data of 4b) after preprocessing.

![Fig. 4a-d Examples of raw and preprocessed data. Image 4a is recorded with 570 nm particles and the Planapo 2x lens. The image 4b is recorded with 1.3 µm particles and the Planapo 1x lens. The intensities for the images are not to scale. Below the corresponding data after preprocessing is shown.](image-url)
5. Evaluation techniques

The evaluation techniques applied are

- Stereoscopic microscopic Particle Image Velocimetry (stereo-µPIV) as described in Lindken et al. (2006). Stereoscopic µPIV measurements provide all three components of the velocity vector in a two-dimensional plane (of a finite thickness). A full 3D measurement is achieved by a scan in the direction normal to the measurement plane.
- Three-dimensional micro particle tracking velocimetry (3D-µPTV) as described in Dracos (1996), but with only two cameras. Dracos recommends at least 3 cameras, but measurements with only two cameras are possible at lower seeding density.
- Tomographic µPIV as described by Elsinga et al. (2005a, 2005b), but with only two cameras. Elsinga et al. (2005a) show that the use of two cameras decreases the reconstruction accuracy.

The different evaluation techniques require different characteristics of the raw data. For that reason we measured the flow in two configurations as shown in Fig 4. For all methods the small angle between the cameras is a limiting factor in the accuracy of the vector field.

5.1 Stereoscopic microscopic Particle Image Velocimetry

For stereo-µPIV the flow is volume illuminated and the depth-of-correlation determines the depth of the measurement region (Meinhart et al, 2000). A small depth-of-correlation is favorable to reduce the influence of velocity gradients on the measurement. Westerweel (1997) has shown that velocity gradients in the direction normal to the measurement plane result in an increase of the RMS of the measured displacements. For PIV methods a high particle image density is required. Keane and Adrian (1992) and Westerweel (2000) describe optimum seeding densities that usually cannot be reached in µPIV applications. The two main reasons for low particle image density are a small depth of focus and an increase of background noise from illuminated out-of-focus particles at very high seeding density. As a consequence the seeding density has been chosen in a way that there is still a sufficient signal-to-noise ratio in the raw data. The use of smaller tracer particles improves the particle image density at constant or reduced void fraction of particles. Westerweel (1997) derives that the optimum particle image diameter is 2 pixel. Due to diffraction limited optics this value cannot be achieved in high-magnification optical configurations. Wereley and Meinhart (2005) give an overview of particle image size at typical microscopy conditions. In our optical configuration the particle image diameter was 4 to 5 pixel.

Lawson and Wu (1997) show that the accuracy for the stereoscopic measurement of the out of plane component depends on the angle $\alpha$ between the two cameras, or viewing directions respectively. For small viewing angles the error of the out-of-plane component increases. At an angle of $\alpha = 45^\circ$ the error is minimal. Such a large viewing angle cannot be achieved with current commercially available stereomicroscopes.

The dominant error source for stereoscopic measurements is the small angle between the two viewing directions. For that reason we have chosen an available optical configuration with the largest angle. The Leica Planapo 2x stereo lens provides a viewing angle of $2\alpha = 36.6^\circ$ in air at 11.5 times magnification, which results in an angle of $2\alpha = 27.5^\circ$ in water (see Fig. 3). Lawson and Wu (1997) derived that for a moderate angle of $\alpha = 13.8^\circ$ the out-of-plane velocity error is about four times the in-plane velocity error.

The correlation depths of the Leica Planapo 2x lens is computed with the equations given by Olsen and Adrian (2000) with infinity corrected f-number (Meinhart and Wereley, 2003) and an intensity threshold $\varepsilon = 0.05$, based on the RMS of the background intensity fluctuation after image processing divided by the average particle image intensity. This yields a correlation depth for the Leica Planapo 2x lens of 16 µm. The correlation depth can also be determined from the length of disparity correlation streak as part of the self-calibration procedure (Wieneke 2005). The measured
value of the correlation depth is 15 µm ± 5 µm. This shows that the choice of \( \varepsilon = 0.05 \) based on the background image contrast was well chosen.

As tracer particles we have chosen 570 nm fluorescent PEG-coated polystyrene particles. The particles were still visible with the Planapo 2x lens that has a numerical aperture of NA = 0.28. The small particles allow a high seeding density. Fig. 4a) shows raw data obtained under these optical condition. The preprocessed data in Fig. 4c) is used for the Stereo-\( \mu \)PIV evaluation.

5.2 3D micro particle tracking velocimetry

3D-\( \mu \)PTV is used to determine the displacement of individual tracer particles in a flow volume. The observation volume is determined by the depth of correlation of the imaging lens. In contrary to stereo-\( \mu \)PIV a large depth of focus is favorable, in order to map the flow in a deep volume. This can be achieved by the use of low NA lenses. Unfortunately low NA lenses have a lower resolution in terms of linepairs/mm. This results in the restriction to relatively large tracer particles of 1 µm diameter. The large depth of focus of the imaging system offers the possibility to capture the flow over the depth of the channel at one instant of time. In combination with high speed microscopic recording particle trajectories could be determined in 3D and residence times can be measured.

In order to increase the depth of focus we have chosen a Leica Planapo 1x lens with a numerical aperture of NA = 0.14. The depth of correlation for this lens and 1.3 µm diameter tracer particles has been computed to 68 µm and a depth of correlation of 60 µm ± 10 µm has been measured.

Due to the small angle between the cameras the triangulation process of computing the particle position in space is very sensitive to small in-plane variations of the determined particle position in the camera images. The accuracy considerations of Lawson and Wu (1997) can also be applied. A Planapo 1x stereo lens with a low NA has a viewing angle of \( 2 \alpha = 14.8^\circ \) (from the self calibration) or 15.0° (measured with the calibration target) in air or \( 2 \alpha = 11.1^\circ \) in water and an out-of-plane velocity error ten times larger than the in-plane velocity error.

Fig. 4b) shows raw data obtained under these optical condition. The preprocessed data in Fig. 4d) is used for the Stereo-\( \mu \)PIV evaluation. The use of the larger tracer particles has significantly improved the signal quality. Individual particle images can be detected and tracked.

5.3 Tomographic \( \mu \)PIV

Tomographic \( \mu \)PIV uses the same illumination technique as 3D-\( \mu \)PTV. The complete flow volume is illuminated and captured in one measurement. Typically four cameras are used to record a volume with a depth aspect ratio of up to one-third of the total field-of-view. The measurement volume is divided in voxels and the 3D-particle distribution is reconstructed using an iterative MART-algorithm (Elsinga et.al. 2005a). This process is the critical as it requires good optical conditions, a well-chosen seeding density and as well as accurate mapping functions. The voxels are then correlated with a three-dimensional correlation function. Wienke and Taylor (2006) give a description of the accuracy of tomographic PIV.

The image recording needs to be optimized for the accurate 3D reconstruction of the voxels. Also the calibration procedure needs to be very accurate, which is achieved by the accurate translation of the calibration grid in combination with the self calibration procedure. An average residual disparity of ~0.5 pixel has been achieved using self-calibration. The particle image density (in terms of particles per pixel) needs to be similar or slightly lower than for \( \mu \)PIV, but it can be up to one order higher compared to \( \mu \)PTV. Comparable to ensemble averaging in standard \( \mu \)PIV it is possible for stationary flows to add-up the reconstructed volumes of many recording for subsequent computation of a single vector field. This procedure is increasing the particle image density and it is often better (and faster) than averaging vector fields. The depth of the measurement volume is preferably large. For that reason we have chosen for the same optical configuration as for 3D-\( \mu \)PTV. The disadvantage of this configuration is the small viewing angle, which causes the particle images to appear heavily elongated (~20 voxel) in the direction of the optical axis. This reduces
significantly the accuracy of the out-of-plane velocity component as shown later.

Table 1 presents a comparison of the optical configurations used in the experiments presented.

Tab. 1: Optical data for the stereo lenses used in the experiments presented in Lindken et al. (2005a,b) and in this work
* Olsen and Adrian (2000) with infinity corrected f# (Meinhart and Wereley, 2003) and ε = 0.05, based on the RMS of the background intensity fluctuation after image processing divided by the average particle image intensity.
** from self-calibration (length of disparity correlation streak, Wieneke 2005)

<table>
<thead>
<tr>
<th>Lens</th>
<th>Planapo 1x</th>
<th>Planapo 2x</th>
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</thead>
<tbody>
<tr>
<td>Magnification (M)</td>
<td>0.71 to 11.5</td>
<td>1.42 to 23.0</td>
</tr>
<tr>
<td>Numerical aperture (NA)</td>
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<td>0.282</td>
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<td>Working distance in air</td>
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<tr>
<td>Viewing angle 2α in air @ M= 11.5</td>
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<td>36.6°</td>
</tr>
<tr>
<td>Viewing angle 2α in water @ M= 11.5</td>
<td>11.1°</td>
<td>27.5°</td>
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<tr>
<td>Field of view</td>
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<td>800 µm x 600 µm</td>
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<tr>
<td>Depth of focus (measured)</td>
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<td>Depth of correlation (computed)*</td>
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<td>16 µm</td>
</tr>
<tr>
<td>Depth of correlation (measured)**</td>
<td>60 µm ± 10 µm</td>
<td>15 µm ± 5 µm</td>
</tr>
</tbody>
</table>

6. First Results

In Lindken et al. (2006) we have shown that with stereo µPIV an accuracy of 10 % for the z-component of the velocity vector can be reached, while the in-plane components of the velocity have the same accuracy as standard µPIV (~1.5 %). Here we show first results on 3D-µPTV and tomographic µPIV measurements. We plan to present stereo-µPIV reference measurements of the same flow in the oral presentation.

In Fig. 5 first results of the 3D-µPTV evaluation (left) and the tomographic µPIV evaluation (right) at three different z-positions within one measurement volume are presented. The in-plane vorticity is shown color-coded. From one individual 3D-µPTV evaluation we obtain about 2000 vectors in a volume of 800 × 800 × 60 µm³. The data presented in Fig 5 contains the sum of 300 measurements. The measurement volume is subdivided in a regular grid of about 130 × 130 × 10 vector cells, each cell 6 × 6 × 6 voxel, or 3.3 × 3.3 × 3.3 µm³ respectively. Each vector cell is filled up with the vectors of each recording falling into a cell. Double fillings are ignored. After 300 recordings a high percentage of the cells are filled up and the vector field is dense enough for median filtering for false vector removal and spatial filtering for noise reduction. The complete µPTV measurement volume contains about 180,000 vectors.

For the tomographic µPIV evaluation the sum of 10 volumetric reconstructions is used to obtain a suitable particle image density with higher signal-to-noise ratio. Then the volume is divided into
interrogation volumes of $48 \times 48 \times 24$ voxel with 75% overlap with a final vector spacing of $6 \times 6 \times 6$ voxel.

The results of the volumetric measurements are presented in the form of measurement planes for better visibility of the results. The planes in the measurement volume are chosen to the center of the volume at $z \approx 163 \, \mu m$ (in a region of high out-of-plane velocity) and 16.5 $\mu m$ above and below the center of the measurement volume.

A comparison of the data evaluated with 3D-µPTV and tomographic µPIV shows the same velocity and vorticity distribution. The vorticity plot reveals a higher noise level for the tomographic µPIV data, containing the data of only 10 measurements compared to 300 for µPTV.

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**Fig. 5a-f** Results of the 3D-µPTV evaluation (left) and the tomographic µPIV evaluation (right) at three different z-positions within one measurement volume. The in-plane vorticity is shown color-coded.
Fig. 6a-b) Comparison of the z-component of the velocity for 3D-µPTV (left) and tomographic µPIV (right) at \( z = 150 \) µm in the center of the measurement volume. The computed velocity \( V_z \) differs by a factor of \( \sim 2 \).

Fig. 7a-b) A 3D-plot of the streamlines (left) and the \( V_x \) velocity isocontours (right) from the 3D µ-PTV results shows that the measured data is consistent over the whole volume. The strong three-dimensionality of the flow is visible. The \( z \)-scale is stretched. The total volume is about 900 x 600 x 50 µm.

Tomographic µPIV shows a considerably reduced amplitude for the \( V_z \)-component (Fig. 6). Probably this is due to the extremely long reconstructed particle streaks in \( z \)-direction with even longer correlation streaks (~30 pixels long) in combination with a kind of Moire intensity pattern in \( z \) leading to peak locking toward \( dz = 0 \). This effect will be investigated further, but it is obvious that reconstructing a tube of \( 4 \times 4 \times 20 \) voxel from \( 4 \times 4 \) pixel will lead to numerical instabilities. A simple remedy is to smooth the reconstructed volume heavily along \( z \) which reduced the error factor already to 2 as shown below instead of 8 without smoothing.

7. Conclusions

The first results show the current status of 3D micro-scale velocimetry methods. In Lindken et al. (2006) we have proven the accuracy of stereoscopic µPIV. Here we show first results for 3D µ-PTV and tomographic µPIV based on stereoscopic imaging. The data for those measurements has been obtained under difficult optical access in a closed microchannel and with only two cameras under a very small viewing angle of \( 2\alpha = 11.1^\circ \). Besides the missing additional camera views, the small viewing angle is the biggest error source. In the volumetric reconstruction particle images are elongated in the direction of the optical axis, which reduces the accuracy of the velocity measurement in the \( z \)-direction. As of today we cannot quantify the accuracy of tomographic µPIV and 3D-µPTV, but the 3D plots in Fig. 7 show that the measured data is consistent. The comparison in Fig. 5 gives an impression of the good agreement between the methods at least for the in-plane components.
In general the measurement parameters like low particle image density and high particle diameter are advantageous for 3D-µPTV compared to correlation methods, but the small viewing angle of the imaging system also reduces the accuracy. The elongated reconstructed particle images results in erroneous velocity calculations for the 3D-correlation-based tomographic µPIV.

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