

On the challenges of precise velocity measurements in transparent pipes using robotic volumetric LPT with Shake-the-Box

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ABSTRACT

In this study, a comparison between measurements in a transparent pipe with and without arbitrary optical distortions using robotic volumetric Lagrangian Particle Tracking (LPT) is presented. Here, the coaxial volumetric velocimeter (CVV) in combination with a robotic arm enables the measurement from the outside (air and acrylic wall) and the inside (only air) of the tube at the end of the pipe section. Experimental results from the pipe flow using helium-filled soap bubbles (HFSB) as tracers and Shake-the-Box (StB) algorithm for the three-dimensional LPT data analyses are presented. A calibration plate with a high spatial resolution was used at every position of the independent views (sub-volumes) for the measurements with arbitrary optical distortions. The evaluations shows that a complete calibration set, consisting of a geometrical calibration and a volume self-calibration, for every sub-volume is mandatory. For comparison, the total number of recorded double frames is varied in order to study the effect on the velocity fields. In this case, 1000 double frames are a good compromise between accuracy and storage space. Moreover, only half of the particle tracks are present in the case with optical distortions (acrylic wall).

1. Introduction

In most industrial applications cost- and time-efficiency plays a major role in the selection of the measurement technique. On the other hand as much as possible information should be collected during a single measurement. Therefore, robotic volumetric LPT measurements have a great potential as a preferred system for numerous fluid dynamic applications in the industry.

Most of the industrial flows take place in nontransparent systems with variable shapes. The only way to measure these flows with techniques like Particle Image Velocimetry (PIV) or Particle Tracking Velocimetry (PTV), from which the LPT is derived, is to install an optical access in the area of interest. In pipe flows acrylic tubes are commonly installed. Due to their large refractive index differences, the curvature and the inhomogeneity of the shape, as a result of the production process, strong optical distortions are present.

Optical distortions can be minimized or even prevented by refractive index matching the working fluid and optical access material (Bai & Katz, 2014, Wright et al. 2017) and by reducing the material

thickness (Fernandes et al. 2021). The latter one is limited by a minimum wall-thickness to withstand the acting forces, impeding a complete prevention of the optical distortions. Matching the refractive index can lead to outstanding results (Michaelis et al 2021). Nevertheless, under industrial conditions spatial, time and cost restrains usually prevent the application of index matching. For some cases index matching cannot be applied, e.g. if the index matching fluid has not the required fluid properties, is corrosive or toxic or is very expensive. Moreover, for gases (e.g. air) index matching is not possible, as there are no solid materials with a refractive index close to unity.

In most experiments all three velocity components in a plane are measured like in pipe flows, combustion engines and blood vessels, among others, a Scheimpflug-adaptor is used to match the plane of focus to the desired plane for tilted camera perspectives, as commonly used in stereoscopic PIV. For example Fernandes et al. 2019 investigated the aortic valve tilt angle on the flow pattern in the ascending aorta region using stereoscopic PIV, Ostovan et al. 2019 performed measurements in a von Kármán turbulence experiment using 4D PTV, Braun et al. 2019 investigated the flow in a combustion engine using High-Speed Tomo-PIV and Michalis et al. 2021 presented results from a pipe flow experiment using four cameras and STB.

In the use case a prevention of optical distortions is not possible. Therefore, a comparison between measurements with and without optical distortions, in the same geometry and at the same position, is carried out in order to assess the accuracy of such measurements and determine the influence of the optical distortions. Here, the CVV allows the measurement without using Scheimpflug-adapters. The measured velocity profile of the turbulent pipe flow is compared to theory via the von Kármán interpolation formula (von Kármán 1921) :

$$\frac{u}{u_{\infty}} = \left[1 - \left(\frac{r}{R} \right)^m \right]^n \quad (1)$$

with $1.25 \leq m \leq 2$ and $n = 1/7$.

2. Experimental Setup

Measurements were conducted with part of the calibration wind tunnel at the Volkswagen AG in Wolfsburg. The facility is an open jet wind tunnel (Airflow Developments Ltd.) with a nozzle exit diameter of 152 mm. A motor rated power of 1.5 kW enables wind speeds between 1 and 30 m/s. A 2000 mm long acrylic tube with an inner diameter of 144 mm and a wall thickness of 3 mm is

centered 800 mm behind the radial fan of the calibration wind tunnel (Fig. 1). A flow straightener is installed close to the beginning of the acrylic tube.

The flow velocity was set to 10 m/s with an impeller anemometer (Mini Air 20, Schiltknecht). Based on the inner tube diameter a Reynolds number of $Re = 96,644$ is obtained.

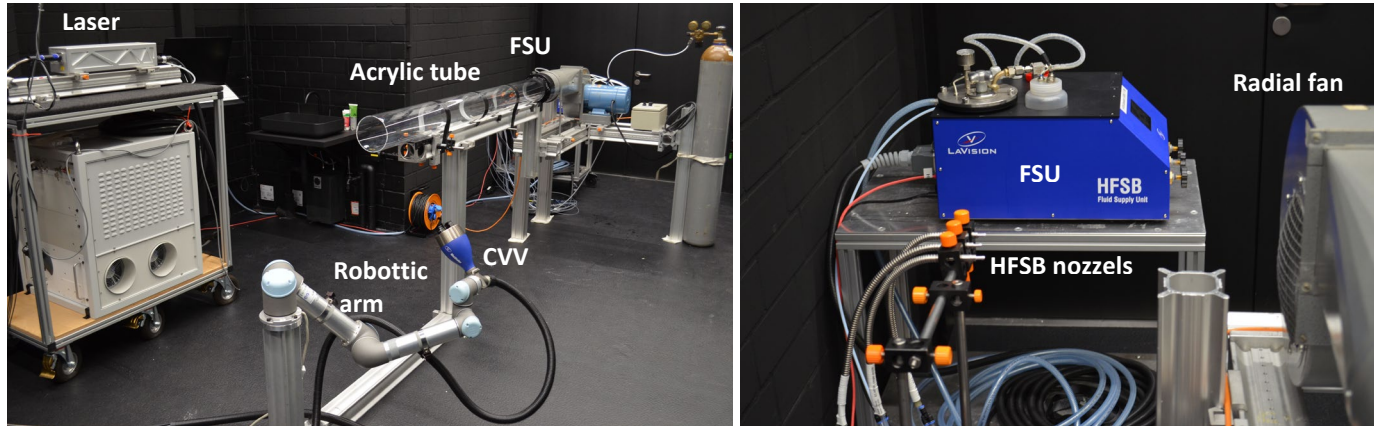


Fig. 1: Overview of the experimental set up (left). Detailed view of the Fluid Supply Unit (FSU) and the single HFSB-Nozzels (right).

For the acquisitions of the recording the CVV probe MiniShaker Aero (Fig. 1, left) from LaVision was used. It exhibits four CMOS-Cameras with a frame rate of 100 Hz at full resolution of 1920×1280 pixels with macro planar lenses (f -number = 6, $f\# = 25$ mm) and a pixel pitch Δp_x of $4.8 \mu\text{m}$. In addition, the MiniShaker incorporates lenses for the volumetric expansion of the laser. The focal point of the cameras was set at 450 mm away from the center of the front cap.

Illumination is provided by a Litron Bernoulli Nd:YAG laser with an output energy of 50 mJ per pulse at a wavelength of 532 nm and a frequency of 100 Hz. The laser is connected through a coupler and an optical fiber to the MiniShaker's head. A typical volumetric field of view starts at $z = 360$ mm with a FOV of $150 \times 70 \text{ mm}^2$ which extends to $230 \times 130 \text{ mm}^2$ at $z = 540$ mm. Synchronization between the laser and the cameras is assured by a PTU X from LaVision.

The MiniShaker heads position and orientation are controlled by a robotic arm UR5 from Universal Robots (Jux et al. 2018) with six degrees of freedom. Position repeatability is stated by the manufacturer as ± 0.1 mm (Universal Robots 2014). The robot is installed at one base positions for all measurements (Fig. 1, left).

Helium Filled Soap Bubbles (HFSB) were used as tracer particles with a mean size of $300 \mu\text{m}$. A HFSB generator from LaVision was used to generate the seeding particles. The system (Fig. 1, right) consists of a fluid supply unit (FSU), three single nozzles and a power supply unit (included

in FSU). Each nozzle produces 40.000 soap bubbles per second. The nozzle were positioned 400 mm away from the inlet of the radial fan.

A single-plane calibration plate (Fig. 2, right), mounted to optomechanical components, is used for the geometric calibration. The calibration plate consists of 1750 dots with a center-to-center spacing of 4 mm and a dot diameter of 2 mm. The calibration plate is inserted at the free end of the tube and can be rotated 360 degrees, to provide a calibration plane for all viewing positions.

After the geometric calibration a volume self-calibration (Wieneke 2008) followed by the determination of the optical-transfer-function (OTF) (Schanz et al. 2012) with the use of experimental data in DaVis 10.2.0 is performed.

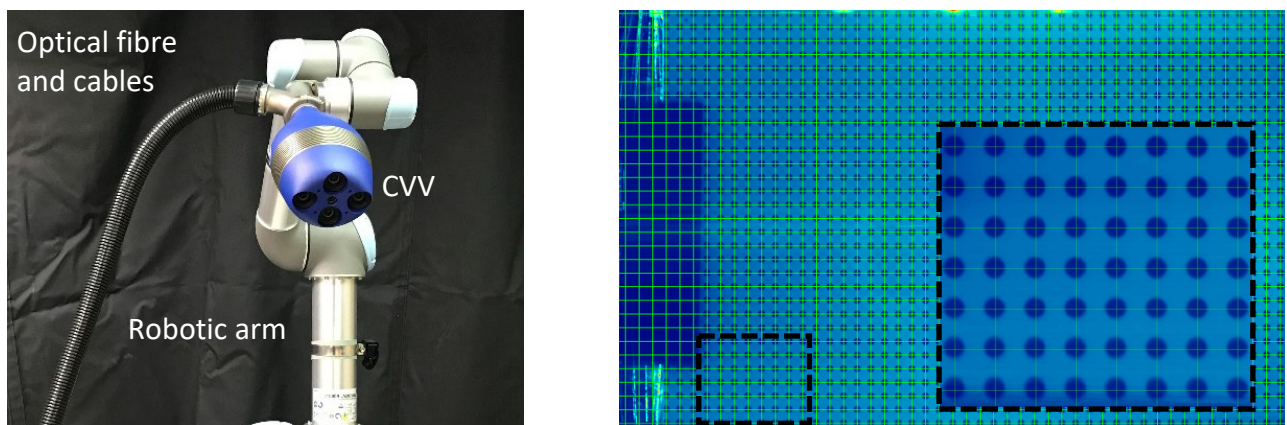


Fig. 2: The coaxial volumetric velocimetry (CVV) probe called MiniShaker Aero held by a robotic arm (left) and dewarped image of the 2D calibration plate with 4 mm dot spacing inside the acrylic tube (right).

To measure the flow field five camera perspectives (sub-volumes) were defined for Case 1 and four for Case 2 (Fig. 3). At each position, 3000 double frame images are recorded at a recording rate of 50 Hz. The measurement positions overlap (Fig. 3, right) at the end of the pipe section for a pipe length of 20 mm. All results were extracted at the middle of the overlapping area. Raw particle images are prepared for the analyses algorithm using the image pre-processing routine in DaVis 10.2.0. Main goal of the pre-processing is the removal of background noise from the image in order to have clearly defined particle images with high contrast between the particles and the background. After the image pre-processing the particle images are analyzed with the Shake-the-Box algorithm (Schanz et al. 2016b) implemented in DaVis. Every sub-volume of Case 1 contains approximately 1.300.000 particle tracks, corresponding to a particle image density of 3×10^{-3} particles per pixel. For Case 2 every sub-volume contains approximately 2.250.000 particle tracks, corresponding to a particle image density of 4×10^{-3} particles per pixel.

After the particles are tracked, the sub-volumes are merged together and time-averaged velocities on a three-dimensional grid are calculated using binning with a bin size of $64 \times 64 \times 64$ voxel at

75% overlap- resulting in a 16 voxel vector spacing. After the binning process vector post processing 3D was applied with the default values (Threshold: 2.5, Allowed epsilon: 0.1 vox., Neighbors: 5x5x5, Min. required: 6) in DaVis.

In order to study the effect of different numbers of recorded images, all prescribed steps were executed for 1000, 2000 and 3000 recorded images.

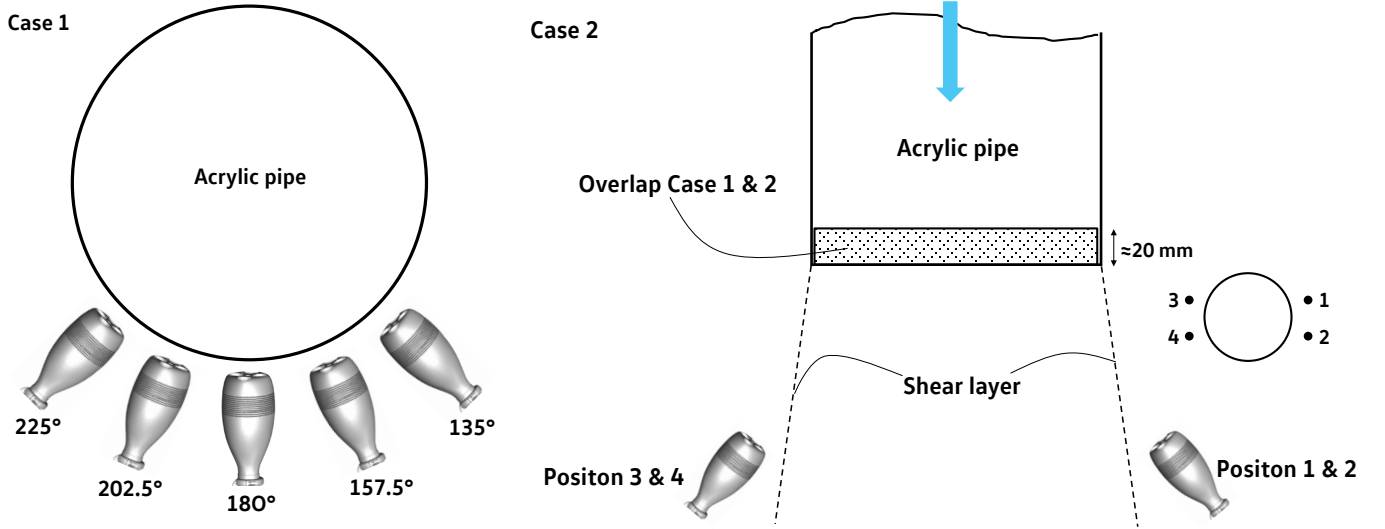


Fig. 3: Positions of the CVV-probe for the measurements through air and acrylic (left) and only air (right).

The dynamic spatial range DSR is defined as the ratio between the largest and the smallest measurable length scales (Adrian 1997). For the present setup the largest length scale is given by the length of the measured volume for Case 1 and the smallest length scale is given by the smallest used bin size.

$$\overline{DSR} = \frac{190 \text{ mm}}{6.9 \text{ mm}} = 27.5 \quad (2)$$

Another important parameter is the dynamic velocity range (DVR). The DVR is defined as the ratio between the maximum resolvable velocity and the minimum one (Adrian 1997). In the present case the ratio between the maximum measured velocity inside the pipe and the measurement uncertainty in the overlapping region of adjacent subvolumes.

$$\overline{DVR} = \frac{10.5 \text{ m/s}}{0.52 \text{ m/s}} = 20.2 \quad (3)$$

3. Results

To analyze the effect of using only one geometric and one volume-self-calibration calibration for all five subvolumes (Case 1), a calibration set for the 180° subvolume was used. It can be seen that for the subvolumes 202.5° and 225° particle tracks were also found, but much less compared to 180°. For the subvolumes 135° and 157.5° no particles were found, even with triangulation errors greater than 2. This, of course, is only valid for the specific positions around this pipe. Every acrylic pipe has its own deviations from the perfect form and therefore individual optical distortions. Hence, it is of fundamental importance to execute a calibration for every subvolume.

The max. number of particles per bin is two times higher for Case 2 compared to Case 1. In the pipe center ($x = 0$, $y = 0$) the number of particles is up to two magnitudes higher in Case 2. The low number of particles in the vicinity of the pipe axis of Case 1 is a clear result of the reflections of the coaxial arrangement. In Case 2 the number of particles is much smaller in the upper and lower part of the pipe, which is supposed to be mainly due to the horizontally distribution of the seeding nozzles. Moreover, decreases the number of particles close to the pipe walls.

Differences in the main velocity w are shown in Fig. 5. A delta of 0.9 m/s between Case 1 and 2 is present. Here, Case 1 has a higher velocity of 0.5 m/s compared to the impeller anemometer whereas the velocity of Case 2 is 0.4 m/s lower. The flow velocity at the wall (2-4 mm) is not zero for both cases, which is most likely due to the decreased number of particles per bin in the wall region and the accuracy of the stitching process (high gradient).

From the graph in Fig. 6 it can be seen that 1000 double frames for each of the four cameras are sufficient in areas with a sufficient number of particles per bin. More double frames only slightly change the velocity profile and on the other hand increase the stored data. Compared to theory, in this case the interpolation formula from von Kármán 1921, both cases show an overall good agreement. Case 2 shows a slightly smaller RMSE value compared to Case 1 (Table 1), thus showing the negative effect of optical distortions.

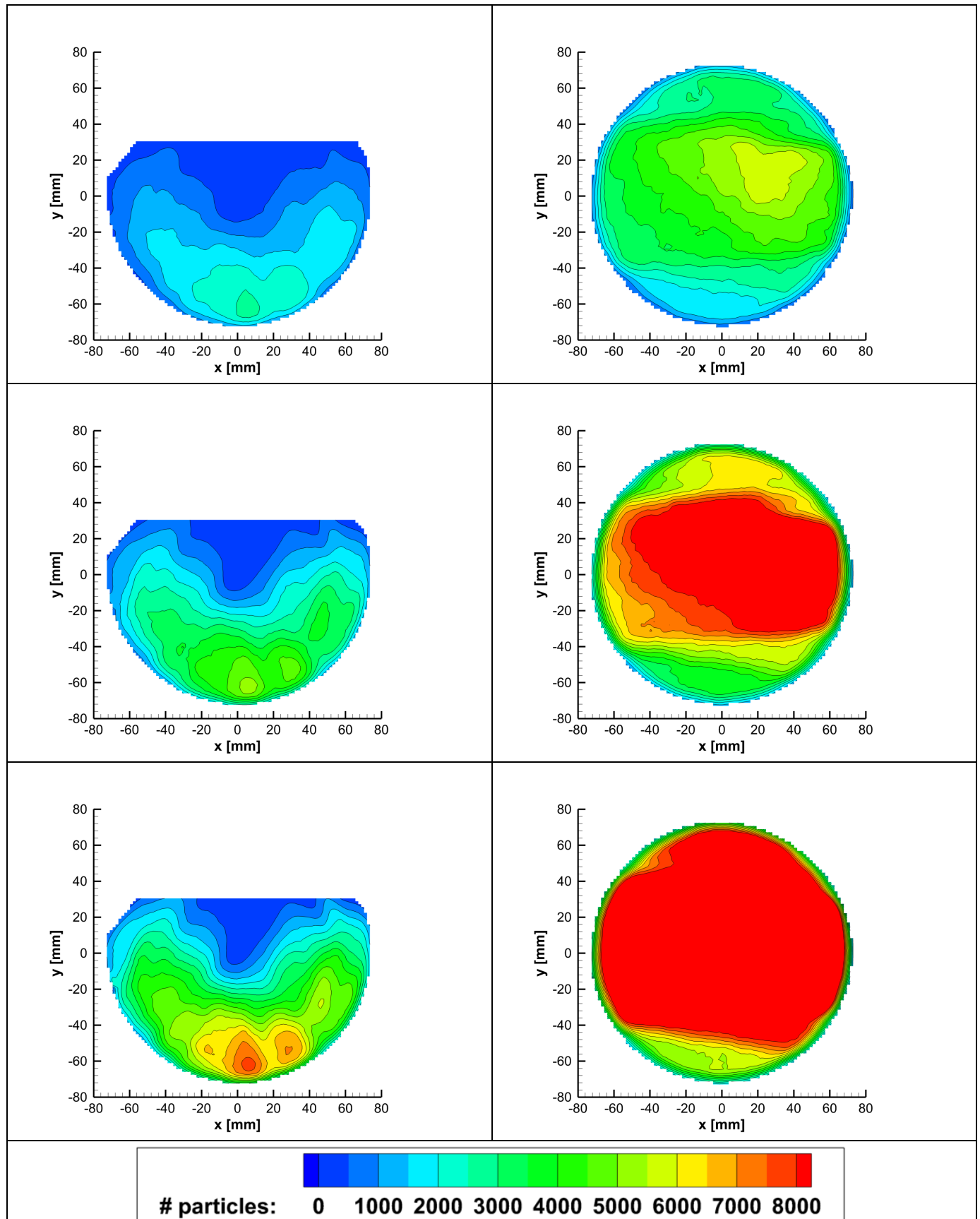


Fig. 4: Number of particles per bin. Case 1 with five subvolumes and optical distortions (left) and Case 2 with four subvolumes and no optical distortions (right). Number of double frames from top to bottom (1000, 2000 & 3000)

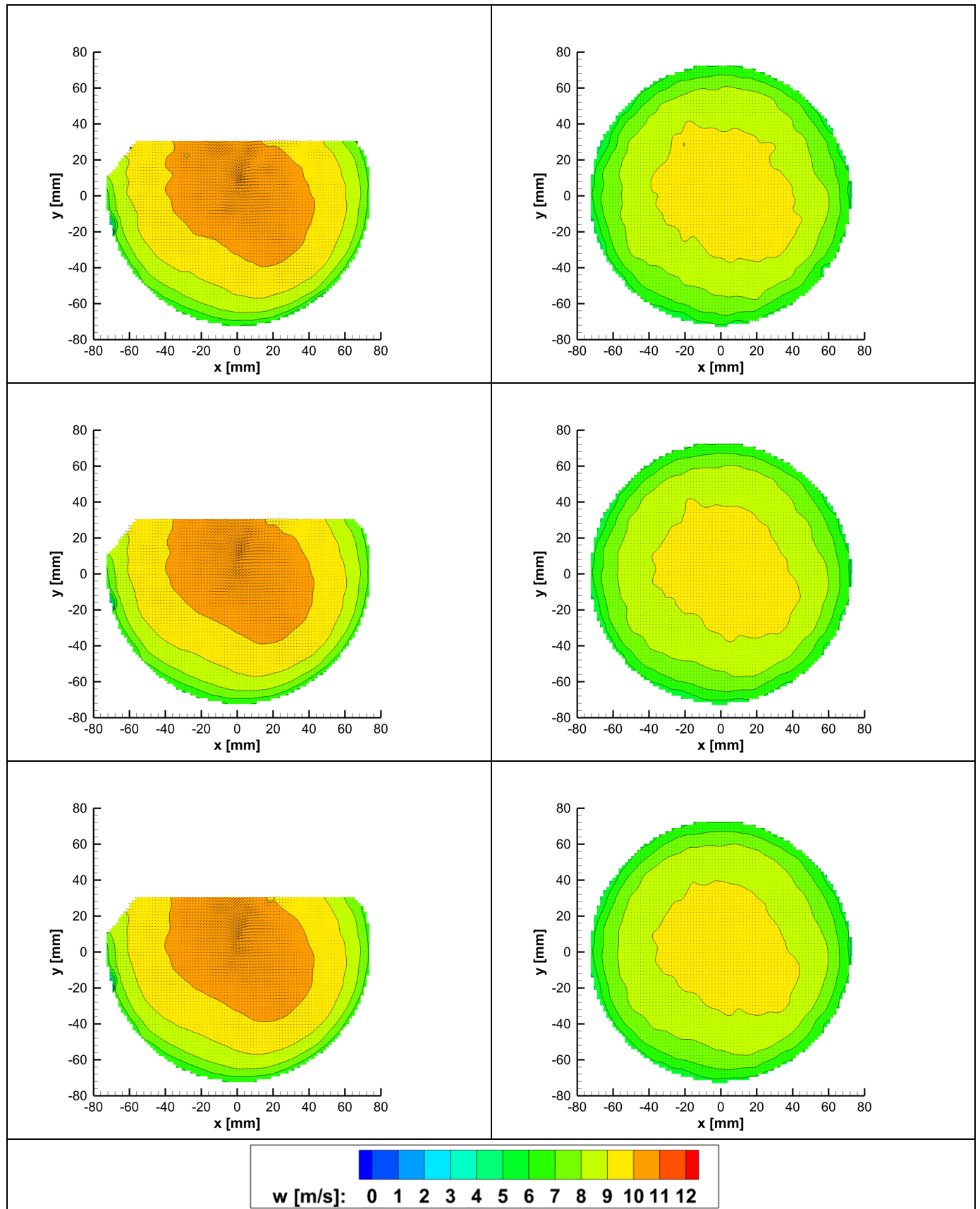


Fig. 5: In plane vectors (u and v) of the average flow field from the middle section of the overlapping area and out of plane component w (color coded). Case 1 with five subvolumes and optical distortions (left) and Case 2 with four subvolumes and no optical distortions (right). Number of double frames from top to bottom (1000, 2000 & 3000)

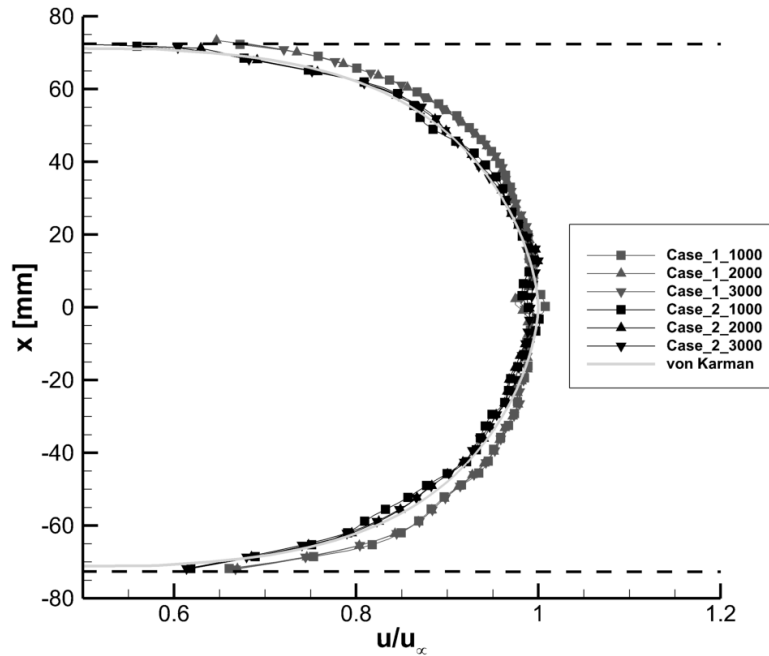


Fig. 6: Comparison of the extracted u -velocity profiles for the different cases and amounts of recorded images at $y = 0$. In comparison to the measured values a theoretical approach von Kármán is presented ($m = 1.6$ and $n = 1/7$). Dashed lines represent the pipe walls.

Table 1: RMSE values for the different cases compared to von Kármán.

	Case_1_1000	Case_1_2000	Case_1_3000	Case_2_1000	Case_2_2000	Case_2_3000
RMSE	0.2339	0.2397	0.2344	0.2058	0.2007	0.2054

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4. Conclusions

In this study, a comparison between measurements in a transparent pipe with and without arbitrary optical distortions using robotic volumetric Lagrangian Particle Tracking (LPT) is presented.

Due to the individual optical distortions coming from the manufacturing process it is mandatory to calibrate every single subvolume.

The recording of more than 1000 double frames for all four cameras only slightly improves the accuracy but also increases the stored data. This can make a big difference in the total storage space on the hard drive.

To increase the number of particles per bin in the vicinity of the pipe axis additional subvolumes with the laser exit not in line with the pipe axis are one possible solution.

It can be seen from the RSME values of the velocity profiles that the difference between Case 2 and the theory is smaller compared to Case 1, thus most likely due to the optical distortions in Case 1. It must be noted that another theoretical approach can lead to minor changes in the velocity profile and therefore, to another result. At the inner wall region both setups are not capable to resolve the flow velocity with an sufficient accuracy. In none of the cases the fluid velocity shows the expected gradients at the inner pipe wall.

Nevertheless, the use of a CVV on a robotic arm with the goal to measure most of the flow field inside a transparent pipe with sufficient accuracy is more than reasonable, despite the inherent optical distortions.

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