PIV for Volume Flow Metering

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Abstract The turbulent flow velocity distribution in a cross section of the German reference standard for volume flow metering devices at the PTB Berlin is measured by LDV and Stereo PIV. The volume flow rate is calculated by integration of the acquired velocity profiles. With proper adjustment of the PIV processing parameters rather low measurement uncertainties for the volume flow rate down to 0.75% are achievable, while LDV produces 0.56%. On average the velocity distributions measured by LDV and PIV deviate less than 10 cm/s from each other (1% of maximum velocity).

1. Introduction

The measurement uncertainty of volume flow meters strongly depend on the velocity profile at the inlet upstream of the metering device [1]. LDV is well established to measure these flow velocity distributions from which the volume flow rate can be calculated through integration of the acquired velocity profiles with high accuracy but is quite time consuming. Stereo PIV is also well suited to measure these types of pipe flows [2]. So a calibrated LDV system with a known measurement uncertainty is used concurrently with a stereo PIV system to acquire the flow velocity distribution across the pipe cross section of the German reference standard for volume flow metering devices at the PTB Berlin [3]. The reference volume flow which is used to compare both methods is determined using a gravimetrically calibrated flow metering device (MID).

2. Setup

All measurement data is acquired at the German reference standard for volume flow metering devices at the PTB Berlin. The measurement uncertainty of this national standard is given with 0.04% for volume flow rates between 3 to 1000 m^3/h [3]. A modified window chamber allows the simultaneous optical access for the LDV and the stereoscopic PIV system and is mounted in the PTB test stand.

The unshifted LDV system uses a 150mW Nd:YAG solid state laser and has a measurement uncertainty of 0.3% in the velocity range of 0.01 – 50.0 m/s. The measurement uncertainty was verified before the measurement campaign by using a rotating disc at the PTB Braunschweig to measure the fringe distortion of the LDV system. The LDV measurement volume is automatically positioned by using a motorized traversing unit, where the coordinates are determined by applying a beam calculation algorithm.

The stereoscopic PIV system consists of two PCO PixelFly CCD cameras with a resolution of 1392x1040, a 30 mJ/Pulse flash lamp pumped Nd:YAG (New Wave Solo I), an articulated arm, standard light sheet forming optics (1 mm waist thickness), a synchronization and timing unit to control the laser and camera timing and PIV evaluation software.

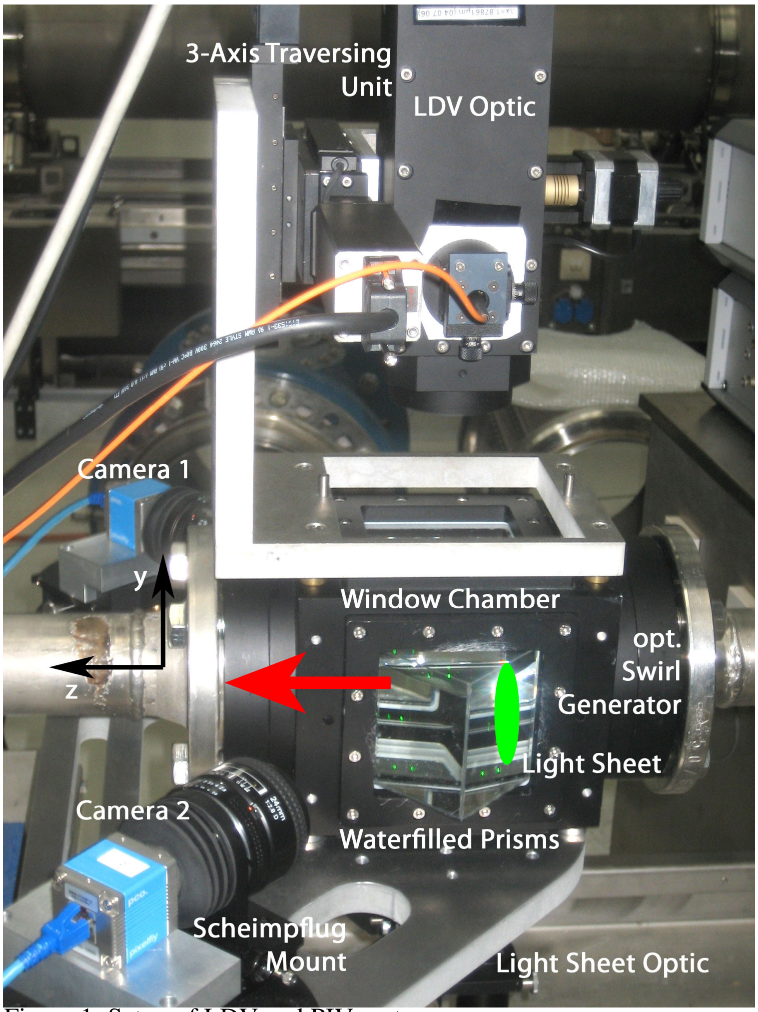

Figure 1: Setup of LDV and PIV system

Access to the pipe section is provided by a glass pipe with a diameter of 55±0.01mm and 2.2mm wall thickness which itself is mounted inside a square, transparent optical access chamber. To minimize optical distortion and to avoid total reflexion at the air/water interface the chamber is equipped with waterfilled prisms on both sides. The light sheet is coupled from the bottom into the chamber, whereas the LDV beams enter the chamber from above. The cameras observe the light sheet in a Scheimpflug configuration, each inclined at 45° to the light sheet plane spanning the cross-section. The calibration of the stereo PIV system with respect to the test section is performed before the chamber is placed into the test faciltity. A grid of markers - which can be translated from the outside to different z positions - is used for calibration. Nine different z positions with a distance of 0.5mm were recorded. In a final step the light sheet is precisely aligned with the target plane positioned at z=0mm. After the calibration procedure the chamber along with the cameras and light sheet delivery device is mounted into the test facility and the LDV system is attached. Hollow silver coated glass spheres with a diameter of 5µm are used as tracer material.

3. Measurement and Data Evaluation

A steady volume flow rate of 80m^3/h was chosen for this investigation. The undisturbed flow velocity is measured first by using the PIV system, where up to 1600 images are acquired with an acquisition frequency of 5Hz, followed by accompanying LDV measurements. Unfortunately simultaneous measurements of both LDA and PIV were not possible due to the strong visibility of the LDA's laser beams in the background of the PIV recordings. Clearly this could have been resolved through the use of laser line filters and a LDA system operating at a different wave length. After completion of the measurement sequence a second series of measurements is acquired with a swirl generator installed upstream of the test section.

For the LDA measurements the system is traversed to 475 positions (19 radii and 24 angles) across the cross section, acquiring about 2000 bursts at each position [1]. The data rate varied around 100Hz in the center, so the flow velocity was at least averaged for 20s – even longer for the positions close to the wall. The probe volume of the LDV optic with f=160mm focal length has a diameter of about 114µm and extends about 811µm along the optical axis. Standard, software-based FFT burst processing is used to retrieve mean velocity data along with standard deviations.

For the stereo PIV system the measurement uncertainty strongly depends on the appropriate use of mapping functions along with suitable algorithms for recombination [4]. The dewarping of the image data prior to standard PIV evaluation ensures a spatially coinciding sampling of the image space from both viewing directions. This permits a straightforward reconstruction of the 3-C vector data from the two 2C vector fields by solving the overdetermined system of equations by accounting for the local viewing directions of the cameras [5]. Another advantage of the dewarping procedure in this application is a simple way of checking the accuracy of the mapping function: the dewarped image of the cross section must be a circle with known radius.

A polynomial of 2nd order and rational functions are used for dewarping. A pinhole model is used to calculate the camera angles and to determine the position of the light sheet inside the chamber [6]. The average of ten camera image pairs are used to calculate the disparity map, which is used by a linear triangulation algorithm [7] to generate a cloud of 3D point coordinates. The vector normal to the light sheet plane is then calculated using the smallest eigenvalue of the covariance matrix of all points [8]. Even bigger variances of the disparity map can be compensated with this method. The position of the light sheet differs from the ideal position between 0.2mm and –0.65mm as illustrated in fig. 2.

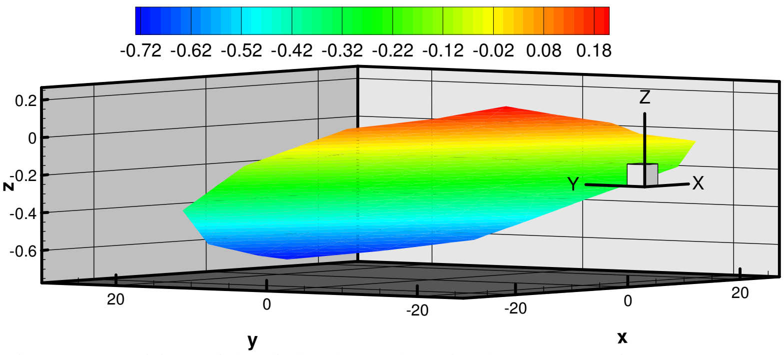

Figure 2: Position of the light sheet plane in the cross section

For PIV processing the first step is the subtraction of the background which is calculated from the ensemble of acquired images. This reduces flare problems near the glass wall and allows the PIV signal recovery close to the wall. A comparatively low seeding density in the test section requires the use of rather quite large interrogation windows for the evaluation of single PIV measurements which in turn limits the spatial resolution. The multi-grid evaluation starts with an interrogation size of 64x64 and is later reducd to 32x32. In this context it was then decided to also investigate the use of ensemble-averaging cross correlation algorithms to evaluate the images as these approaches allow an increase in spatial resolution of the average velocity field even in sparsely seeded (steady) flows provided a sufficiently large number of images is available. In the following the performance of both processing approaches is compared. Standard PIV evaluation is performed with the commercial software VidPIV 4.6XP (ILA GmbH) while the ensemble-average CC is done using PIV software from DLR [9]. In this context it should be noted that the use of ensemble-correlation methods for the reconstruction of three component velocity data has to be observed with caution because it can introduce a velocity bias especially in non-isotropic turbulent flows. Nonetheless this is less critical in the present situation due to the essentially orthogonal viewing directions between the cameras which decouples the measurements from each other and thus allows individual averaging the 2-C velocity data prior to reconstructing the 3-C velocity data.

4. Results

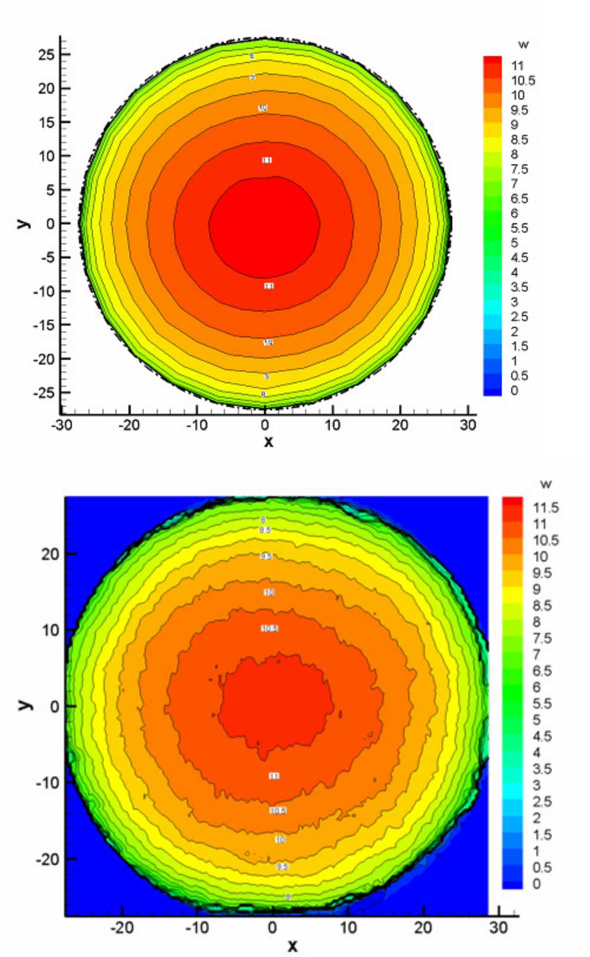

Figure 3: Out-of-plane velocity distribution measured by LDV (top) and PIV (bottom: average CC results)

The out-of-plane velocity distribution determined by LDV and PIV is shown in figure 3. LDV produces a very uniform velocity distribution. The PIV results are a little bit noisier and lower in the absolute velocities for the averaged CC results. To some degree the choice of PIV processing parameters, in particular the size of the sampling window, influences the shape of the turbulent velocity profiles. As expected, larger interrogation spots smear out velocity gradients which are particularly strong near the wall. Thus the largest differences between the LDV and PIV data are found near the wall and for the x profiles. In part the deviation on the x-profiles could also be an artifact of the mapping functions used and the camera angles/positions for the recombination.

In order to compare the two methods the w-velocity distribution is used to calculate the volume flow rate by integration. LDV is well established for the determination of volume flow rates out of turbulent velocity profiles. The reference flow meter determined the flow rate during the complete experiment with 79998.21 l/h (see table 1). The volume flow from integrating the LDV data is 80517 l/h which corresponds to an overall measurement uncertainty of 0.56%. The best PIV result was achieved using the ensemble-averaging cross-correlation techniques (AveCC) with an integral flow rate of 80598 l/h corresponding to a measurement uncertainty of 0.75% (table 1). This result is very close to the uncertainty achieved with LDV.

Q=79998,21 l/h	Q		v	
Method	**Q Integrat.**	**dQ MID-Method**	**w Centre x**	**Error v LDA/PIV**
	l/h	**%**	m/s	**%**
LDV	80517,40	**-0,56**	11,323	**-**
LDV (Swirl)	80955,80	-1,11	12,841	**-**
Ave CC	80597,78	-0,75	11,2	1,09
PIV1uc	81267,44	**-1,59**	11,595	-2,40
PIV2c	80799,35	-1,00	11,609	-2,53
PIV3c (Swirl)	79776,32	0,28	13,306	-

Table 1 summarizes the different evaluation strategies used and the results produced. The token 'uc' is used for uncorrected stereo PIV data, meaning that no disparity correction of the mapping function was performed. The token 'c' indicates the use of corrected mapping functions, so the datum marks for the initial calibration are back-projected by using the pinhole model to the slightly tilted light sheet plane shown in figure 2. PIV1uc is achieved with a multigrid (64x64, 32x32 at 50% overlap) evaluation strategy including window deformation, Whittaker peak fitting and B-Spline reconstruction. The single PIV results are averaged after the evaluation. PIV2c is identical to PIV1uc except for the additionally applied mapping correction. Here the data also exhibits some deformation close to the center line. For comparison with the LDV data the uncorrected data set (PIV1uc) is used (figure 4). The two measurements indicated by “Swirl” are acquired while the swirl generator was installed. Here the unshifted LDV system showed a larger measurement uncertainty due to the high circumferential velocity component. The PIV data (PIV3c) is to close to the reference data which needs to be further investigated. (Corresponding results using the ensemble averaging correlation technique were not yet available at the time this article was written.)

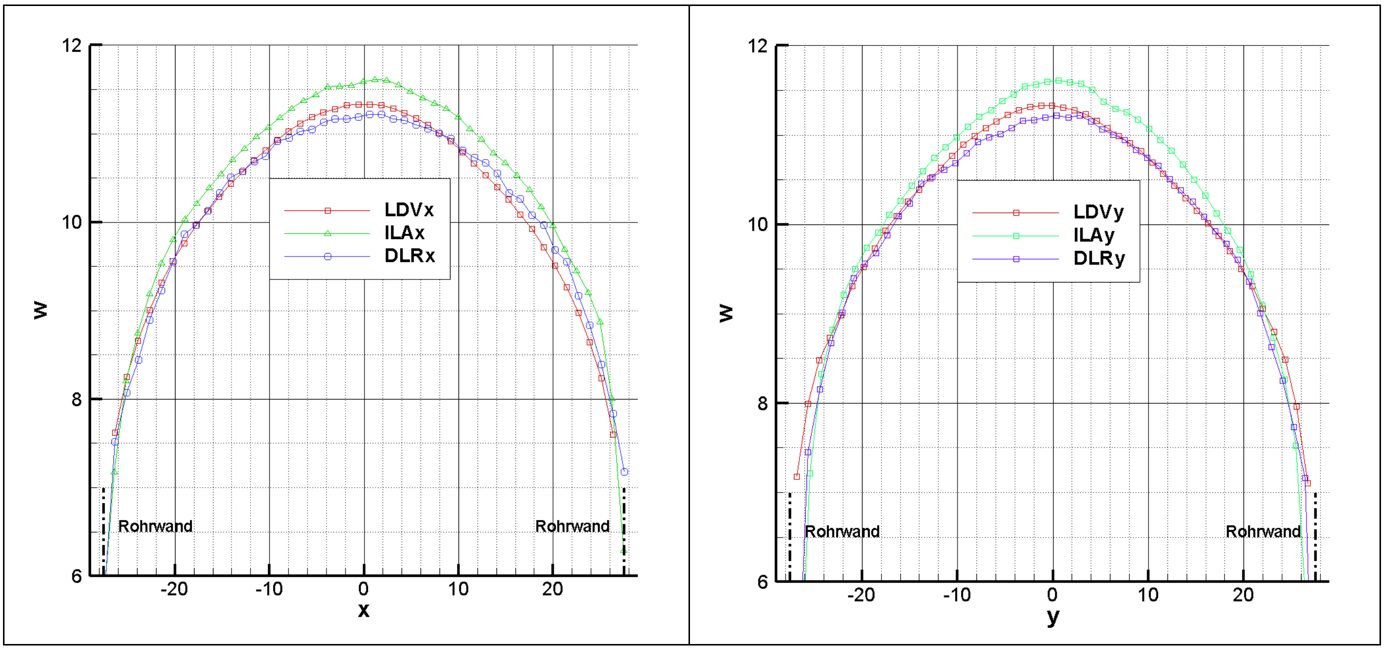

Figure 4: Comparison of the extracted velocity profiles along the x- and y-axis for best Q integration

The data for the standard PIV evalution procedure using single image pairs and averaging the generated vector fields show for the x-axis a nearly constant offset to higher velocities. One reason could be the use of a recombination without looking at the residuals like it was performed for the average cross-correlation results. The PIV data along the y-axis show a better agreement with the LDV data especially near the walls but there are still higher velocities in the center.

The best agreement between LDV and PIV data is provided by the ensemble-averaged cross correlation results. The velocity profiles along the x-axis obtained by PIV show a small velocity lag of ~1% close to the centerline. Near the right hand side the PIV results show a higher velocity than the LDV data. Here the influence of the mapping function and the recombination parameters could be investigated further. A small velocity lag can be as well observed for the PIV results along the y-axis in the centre and the velocity gradient close to the walls in the area from –23mm to –26mm and 22mm to 26mm is not completely resolved.

5. Summary and Discussion

The use of PIV techniques to investigate the inflow conditions for flow meters is quite promising. With standard stereo PIV systems the measurement uncertainty is already close to the established LDV method and has the advantages of a faster acquisition time and that all three components are acquired within one setup. The problem of low seeding densities at typical test conditions can be avoided within limits by using average cross-correlation techniques. Still the number of parameters which needs to be adjusted properly to be close to the LDV results needs an experienced user. The processing time for the PIV data is nearly the same like the additional measurement time for the LDV system but PIV produces all three components during that time. The LDV systems used for profile scanning in volume flow metering applications are working nearly automatically. Here the

PIV system needs some additional application specific development especially considering the time-consuming calibration. However once calibrated a well designed PIV system should require little or no recalibration. Even if mapping correction seems useful in this case to reduce the measurement uncertainty, a proper alignement of the light sheet plane with the cross section is essential for the later determination of the volume flow rate.

6. References

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