Application and Validation of Large Scale Tomographic PIV in a Long Rectangular Convection Cell

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ABSTRACT

Tomographic Particle Image Velocimetry for large scale applications (LST-PIV) is applied to a convection cell to measure the large scale flow structure in forced convection. Different numbers of cameras are considered in the reconstruction procedure to analyse the effect on the accuracy of LST-PIV using experimental data. A two-, three- and four-camera-system is studied at a constant particle density of 0.01 particle per pixel. In order to validate LST-PIV the data is compared to respective planar Particle Image Velocimetry data.

1. INTRODUCTION

A very promising approach to capture the unsteady and three-dimensional flow structures in turbulence is the recently developed Tomographic Particle Image Velocimetry (Tomographic PIV, Elsinga et al. [3]). However, in the past this novel technique was applied only to measurement volumes of the order of ten cubic centimetres (Elsinga et al. [6]). This is e.g. of interest for investigations of time-dependent three-dimensional large scale flow structures in turbulent thermal and mixed convection (Ahlers et al. [1], Kunen et al. [8], Niemela et al. [10], Xia et al. [18], Schmeling et al. [13], Westhoff et al. [16]).

The goal of our study is to demonstrate that the spatial and temporal behaviour of this large scale flow structures in a convection cell can be investigated systematically using Tomographic PIV. Herein, the effect of the number of projections, i.e. the number of camera recordings, used for reconstruction of the three-dimensional intensity distribution on the accuracy of the measurement technique since the resulting flow is statistically stationary and close to two-dimensional. Finally, the volume flow rate is set to 20.1 litres per second, which corresponds to an inlet channel Reynolds number of 530 based on the height of the channel. Here, only forced convection is investigated. This configuration provides an ideal test case for the validation of the measurement technique since the resulting flow is statistically stationary and close to two-dimensional. Finally, the volume flow rate is set to 20.1 litres per second, which corresponds to an inlet channel Reynolds number of 530 based on the height of the channel.

3. CONVECTION CELL

A sketch of the convection cell is shown in Figure 1. The cell has a length of 2.5 m and a cross section of 0.5 m × 0.5 m. The inlet and outlet channels of height 25 mm and 15 mm, respectively, are attached to one side wall. By supplying air, well defined forced convection can be realized in the cell. Here, only forced convection is investigated. This configuration provides an ideal test case for the validation of the measurement technique since the resulting flow is statistically stationary and close to two-dimensional. Finally, the volume flow rate is set to 20.1 litres per second, which corresponds to an inlet channel Reynolds number of 530 based on the height of the channel.

4. MEASUREMENT SET-UP

Figure 1 provides a sketch of the set-up of the LST-PIV system. The measurement volume had a size of approximately 790 mm × 450 mm × 200 mm. It was observed simultaneously by a camera system consisting of four cameras with a spatial resolution of 1392 × 1024 pixel (PCO pixelfly). Each camera was equipped with a focal length of 21 mm lens (Distagon T* 2.8/21, Carl Zeiss). The apertures were set to f/4. Due to the large depth of field there was no need to tilt the camera lenses relative to the image plane according to the Scheimpflug criteria. The camera viewing angles were approximately 30° and 20° in X- and Y-direction with respect to the Z-direction. According to Elsinga et al. [3] these inclinations provide an optimal quality in the reconstruction process. HFSBs with a mean diameter of approximately 0.2 to 0.3 mm were used as tracer particles in the LST-PIV experiment (see Bosbach et al. [2]). In order to guarantee a homogeneous intensity distribution with high quality (Elsinga et al. [3], Wiencke [17]). Finally, the calibration accuracy was achieved by applying the so-called volume self-calibration in an iterative manner (Wieneke [17]).

Furthermore, one should notice that LST-PIV requires a scaling of the complete system. As a consequence certain parameters of the measurement system, which could potentially affect the accuracy, are different compared to the case of small measurement volumes. These are mainly a larger ratio between particle size and wavelength of light, and a larger ratio between particle size and voxel size. Additionally, the opening angle of the camera in the present set-up is larger.
seeding density throughout the complete length of the measurement volume HFSBs were injected at five different positions into the settling chamber in cell length direction. Furthermore, the HFSBs were first blown in an extra settling box of 1.5 m × 0.5 m × 0.5 m in order to homogenize the seeding. Pressurized air was used to blow the bubbles out of the box into the settling chamber. Hence, approximately five percent of additional air was injected into the convection cell as compared to the data of Schmeling et al. [13]. This method still led to a small disturbance of the velocity profile at the channel end of up to 5.5 percent with a \( \text{rms} \) value of 3.8 percent in longitudinal cell direction.

In order to illuminate tracer particles in a volume with defined boundaries a special LED light source suitable for PIV was developed. Further information concerning the LED light source can be found in Kühn et al. [7].

In order to obtain the necessary calibration function, which maps physical coordinates to image coordinates, a calibration target was traversed in \( X \)-direction through the measurement volume. An image of the calibration target was recorded at five different \( Z \)-positions by every camera. A mapping function is obtained according to Soloff et al. [14] by fitting third order polynomials in \( X \)- and \( Y \)-direction and a second order polynomial in \( Z \)-direction using the known marker positions of the calibration target (Kühn et al. [6]). By applying the volume self-calibration (Wieneke [17]) an initial calibration error of up to 1.25 pixel was decreased to an error of less than 0.05 pixel after a few iterations using \( 5 \times 3 \times 2 \) subvolumes.

\[ \text{5. DATA PROCESSING} \]

During the measurement 34 instantaneous flow fields were recorded with a sampling frequency of one Hertz. The average particle density corresponds to 0.01 particle per pixel (ppp), which is relatively low for Tomographic PIV (see Elsinga et al. [3]). First, in order to increase the quality of the reconstructed intensity distribution, the particle projections, i.e. the camera recordings are pre-processed. The image pre-processing, which is similar to the pre-processing of Michaelis and Wienke [9], comprises the following steps:

- subtraction of the minimum image calculated from the complete series of recordings,
- normalisation of intensity by dividing the image by the sliding average calculated with a kernel of 51 × 51 pixel for the complete series of recordings,
- enlargement of particle images by applying a 3 × 3 Gaussian smoothing filter and
- normalisation of the particle image intensity peaks by dividing by the sliding local average (kernel size of 15 × 15 pixel).

In Kühn et al. [7] an example of particle images before and after pre-processing can be found.

In order to reconstruct the three-dimensional intensity distribution in the measurement volume, the Multiplicative Algebraic Reconstruction Technique (MART; Herman and Lent [5], Elsinga et al. [3]) is used. It is implemented as described in Kühn et al. [6]. The measurement volume is discretised by 975 × 585 × 288 voxel. The relaxation factor \( \mu \) of the MART (see equation 3 in Elsinga et al. [3]) is set to one, the intensity distribution is initialised with ones and a bilinear interpolation filter is used.

For reconstruction a four-, three- and two-camera-system is considered, i.e. the three-dimensional intensity distribution is reconstructed from the projections of camera 1, 2, 3 and 4, camera 1, 2 and 3, and camera 1 and 3, respectively (see Figure 1). It should be mentioned that the number of iterations to reach a certain convergence value depends on the number of projections. This is evidenced by the plot of the difference between the displacements of subsequent iterations in Figure 2. The displacements are calculated by cross-correlation of 180 non-overlapping interrogation volumes (IVs) of the reconstructed intensity distribution at two subsequent times.

The size of the IVs amounts to 96³ voxel. For the four-camera-system the reconstruction is sufficiently converged after three iterations (Kühn et al. [7]). Furthermore, in order to reach the same convergence criteria using a three- and two-camera-system five and eleven iterations are necessary, respectively. The peaks in the plot are mainly due to outliers. However, the changes of the displacement are of the order of \( 10^{-2} \) voxel.

According to Elsinga et al. [4] the number of ghost particles in the reconstructed measurement volumes is a function of the seeding density, the size of the particles, the depth of the

\[ \text{Figure 1. Schematic sketch of rectangular convection cell and LST-PIV set-up.} \]

\[ \text{Figure 2. Magnitude of average of absolute difference of displacement in} \ X, \ Y, \ Z \text{-direction between subsequent iterations of the reconstruction process (○ – four-, ▲ – three-, O – two-camera-system). Average is calculated from values of 180 non-overlapping IVs of one instantaneous flow field.} \]
PIV system, the mean velocity profile of the reconstruction procedure on the accuracy of the LST-PIV. In order to analyse the effect of the number of projections used rises from seven over eight to 13 percent. The number of outliers decreases with decreasing number of cameras from 0.38 over 0.30 to 0.12. Accordingly, the number of outliers coefficient decreases with decreasing number of cameras from 0.067 m/s, gray to 0.098 m/s and light gray to 0.110 m/s.

reconstructed measurement volume and the number of cameras used for reconstruction. In the actual case only the latter is not constant. Applying equation 3 given in Elsinga et al. [4] the estimated number of ghost particles per real particle amounts to 0.1, 1.8 and 45.5 in the four-, three- and two-camera-system, respectively. After reconstruction, two subsequent three-dimensional intensity distributions are cross-correlated using three-dimensional Fast Fourier Transformations. In order to do so IVs of 96³ voxel or 74³ mm³ are used. Hence, each IV comprises approximately 32 real particles according to the particle density of 0.01 pp. The overlap of the IVs is set to 75 percent. Moreover, an iterative multi-pass algorithm is used. Five iterations are performed applying a deformation of the reconstructed intensity according to the local velocity field as described by Raffel et al. [12] and Scarano [13] in the two last iterations. For intensity interpolation fifth order B-Spline functions (Raffel et al. [12], Thévenaz et al. [15]) are used. In order to detect the peak in the correlation volume with sub-pixel accuracy, one-dimensional three-point Gauss fits are applied in X-, Y- and Z-direction.

Details of the set-up and evaluation of the planar PIV data are documented in Schmeling et al. [13].

6. RESULTS

In Figure 3 the mean velocity field in the measurement volume obtained by averaging 34 instantaneous LST-PIV velocity fields of the four-camera-system is shown. Iso-surfaces of the velocity magnitude visualise the global structure of the flow field. Clearly, a roll-like structure can be identified. In the measurement volume (average of 34 samples, four-camera-system). Iso-surfaces show velocity magnitudes. Dark gray corresponds to 0.067 m/s, gray to 0.098 m/s and light gray to 0.110 m/s.

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In order to analyse the effect of the number of projections used in the reconstruction procedure on the accuracy of the LST-PIV system, the mean velocity profile of the Y-component at

\[ Y = 250 \text{ mm} \]

is plotted as function of \( t \). LST-PIV data for different numbers of cameras and planar PIV data are compared. From both measurements a linear velocity gradient, which reflects the large scale roll structure, can be clearly identified. In the middle of the convection cell (\( Z = 250 \text{ mm} \)) \( v_Y \) is close to zero. At the outer border of the measurement volume (\( Z = 450 \text{ mm} \)) the velocity component is approximately -0.16 m/s.

\( X = 1562 \text{ mm} \) and \( Y = 250 \text{ mm} \) is compared to respective planar PIV data measured by Schmeling et al. [13]. As already discussed in Kühn et al. [7] a small difference between planar and LST-PIV data exists even for the four-camera-system. The differences are a result of the not yet fully converged flow statistics and to a small extent of disturbance of the inflow due to tracer particle injection. In this paper only the differences between the results due to different numbers of cameras used for evaluation are discussed in detail.

A normalised velocity denoted by \( v' \) is defined additionally in order to consider the accuracy of LST-PIV. \( v' \) is normalised with the voxel size \( h \) and the separation time \( \Delta t \) between the recordings so that \( v' = 1 \) corresponds to a particle displacement of exact one voxel.

In Figure 4 the mean velocity component in Y-direction, is plotted as function of Z. LST-PIV data for different numbers of cameras and planar PIV data are compared. From both measurements a linear velocity gradient, which reflects the large scale roll structure, can be clearly identified. In the middle of the convection cell (\( Z = 250 \text{ mm} \)) \( v_Y \) is close to zero. At the outer border of the measurement volume (\( Z = 450 \text{ mm} \)) the velocity component is approximately -0.16 m/s.

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Obviously, the data between the LST-PIV data and the planar PIV for the four- and three-camera-system are nearly identical as can be seen from Figure 4. The data differ by less than \( \Delta v_Y \) = 0.06 (inset of Figure 4). Thereby the data of the four-camera-system are slightly closer to the planar PIV data than the data of the three-camera-system. However, for the two-camera-system the velocity gradients become smaller. Hence, the deviation to the planar PIV data increases (inset of Figure 4). Differences of up to \( \Delta v_Y \) = 1.26 exist. The linear trend in the dependence of \( \Delta v_Y \) over \( Z \) indicates the velocity profile is rotated around the middle of the measurement volume.

On the other hand, when comparing the velocity profile of the Z-component as function of \( Y \) in the middle of the measurement volume (\( X = 1562 \text{ mm}, Z = 350 \text{ mm} \); as done for different sizes of IVs in Kühn et al. [7]), the differences between the data of the four-, three- and two-camera-system are less than \( \Delta v_Z \) = 0.09 except for some positions which are affected by outliers. For the sake of brevity the comparison is not shown.
It should be mentioned again that for the two-camera-system the estimated number of ghost particles increases 25 and 455 times compared to the three- and four-camera-system, respectively, which potentially affect the measurement accuracy. Finally, it seems as the difference of the two-camera-system to the others in the velocity plot as function of Z (Figure 4) is systematic with a negligible difference in the middle of the measurement volume. The reason for this is not yet clear. However, more detailed investigations are necessary in order to find the reason for this behaviour.

7. CONCLUSIONS AND OUTLOOK

LST-PIV is applied to a convection cell to measure the large scale flow structure in forced convection. Different numbers of cameras are considered in the reconstruction procedure to analyse the effect on the accuracy of LST-PIV using experimental data. A two-, three- and four-camera-system is studied at a constant particle density of 0.01 ppp. In order to validate LST-PIV the data is compared to respective planar PIV data. It is noticed that the number of iterations necessary for reconstruction strongly depends on the number of cameras. For all numbers of cameras the global flow field is properly predicted. The difference between the results of the four- and three-camera-system is less than $|\Delta v_z| = 0.06$. On the other hand, the difference of the data of the two-camera-system to the planar PIV data is larger. Differences of up to $|\Delta v_z| = 1.26$ exist. This is only observed in the velocity profile in the depth direction of the measurement volume. The reason for this is not yet clear. However, more detailed investigations are necessary in order to find out if this is a result of the two-camera-system or the number of ghost particles.

Furthermore, in the future the particle injection method will be improved and the particle density and number of samples will be increased. Finally, more variations of the experimental set-up are planned in order to analyse the effects on the accuracy of LST-PIV. This includes changing the seeding density and thickness of light volume as function of the number of cameras.

REFERENCES


