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Published on: 01 Sep 2019 - Experiments in Fluids (Springer Berlin Heidelberg)

Topics: Particle image velocimetry, Boundary layer, Adverse pressure gradient, Water tunnel and Ray tracing (graphics)

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Publication date
2018

Document Version
Final published version

Published in
Proceedings of the 19th International Symposium on Application of Laser and Imaging Techniques to Fluid Mechanics

Citation (APA)
Zhao, Z., Buchner, J., Ding, J., Shi, S., Atkinson, C., & Soria, J. (2018). Volumetric measurements of a self-similar adverse pressure gradient turbulent boundary layer using single-camera light-field particle image velocimetry. In Proceedings of the 19th International Symposium on Application of Laser and Imaging Techniques to Fluid Mechanics (pp. 3070-3078). Lisboa, Portugal: Instituto Superior Técnico.

Volumetric measurements of a self-similar adverse pressure gradient turbulent boundary layer using single-camera light-field particle image velocimetry

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Keywords: Light-Field PIV; 3D PIV; Turbulent Boundary Layer; Adverse Pressure Gradient

ABSTRACT

As a novel volumetric particle image velocimetry technique, single-camera light-field PIV (LF-PIV) is able to reconstruct three-dimensional flow fields with a single camera. The merits of LF-PIV lie in its concise hardware setup and minimum optical access requirement, its capability has been proved in many flow scenarios. In this study, LF-PIV is used to measure a self-similar adverse pressure gradient turbulent boundary layer (APG-TBL). Experiments were performed in a large water tunnel at the Laboratory for Turbulence Research in Aerospace and Combustion (LTRAC), Monash University. 20 independent batches of light-field PIV images were captured for both inner and outer flow, each consisting of 250 instantaneous image pairs. Instantaneous 3D velocity fields were reconstructed with the GPU accelerated DRT-MART and 3D cross-correlation methods and compared with two-dimensional PIV (2D-PIV) results. Initial results show that though limited by the experiment conditions and PIV algorithms developed in 2016, we still can have similar accuracy to 2D-PIV near and above the boundary layer. With the volumetric calibration method that compensates optical distortions caused by lens defect and misalignment between the micro-lens array (MLA) and image sensor, the resolution of LF-PIV is sure to have a large improvement.

1. Introduction

Particle image velocimetry technique evolved from 2-dimensional (2D) measurement into volumetric measurements. As a new volumetric particle image velocimetry technique, the single-camera light-field PIV (LF-PIV) (Ding et al. 2015, Fahringer et al. 2015, Shi et al. 2016a) has been successfully applied in many complex flow scenarios to get three-dimensional flow fields (Li et al. 2017, Xu et al. 2017, Bolton et al. 2017). Given sufficiently high pixel and MLA resolution, LF-PIV can achieve similar accuracy levels as Tomographic PIV (Tomo-PIV), but requires much simpler hardware setup and less optical access (Shi et al. 2017b).

The motivation of the present study is to apply the LF-PIV technique to an adverse pressure gradient turbulent boundary layer to demonstrate its measurement resolution. The experimental arrangement is presented in the next section, followed by the LF-PIV data processing procedure and the boundary layer statistical properties. At the end, a brief introduction of the new volumetric calibration method for Light-Field PIV and the way to improve the experiment results will be discussed.

2. Experimental Environment

This experiment was carried out in the 0.5 × 0.5 × 5.5 m water tunnel at the Laboratory for Turbulence Research in Aerospace and Combustion (LTRAC), Monash University. For the LF-PIV experiment, this facility was adjusted to be in the same condition as the measurement in Atkinson et al (2016a, b). The water tunnel was homogenously seeded with approximately neutrally buoyant hollow glass spheres (Potters, 11μm). A test volume measuring 61.3×12.8×10 mm was uniformly illuminated by a double pulse Nd:YAG laser (Gemini PIV 15, 90 mJ/pulse, 532 nm). The particle images were captured by an in-house 29M pixel light-field camera based on an Imperx B6640 fitted with a Micro-NIKKOR 200mm lens (Shi et al. 2016b, Shi et al. 2018). The light-field camera was setup in section 4, 3.68 m downstream of the tunnel entrance, and focused on the center plane of the tunnel.

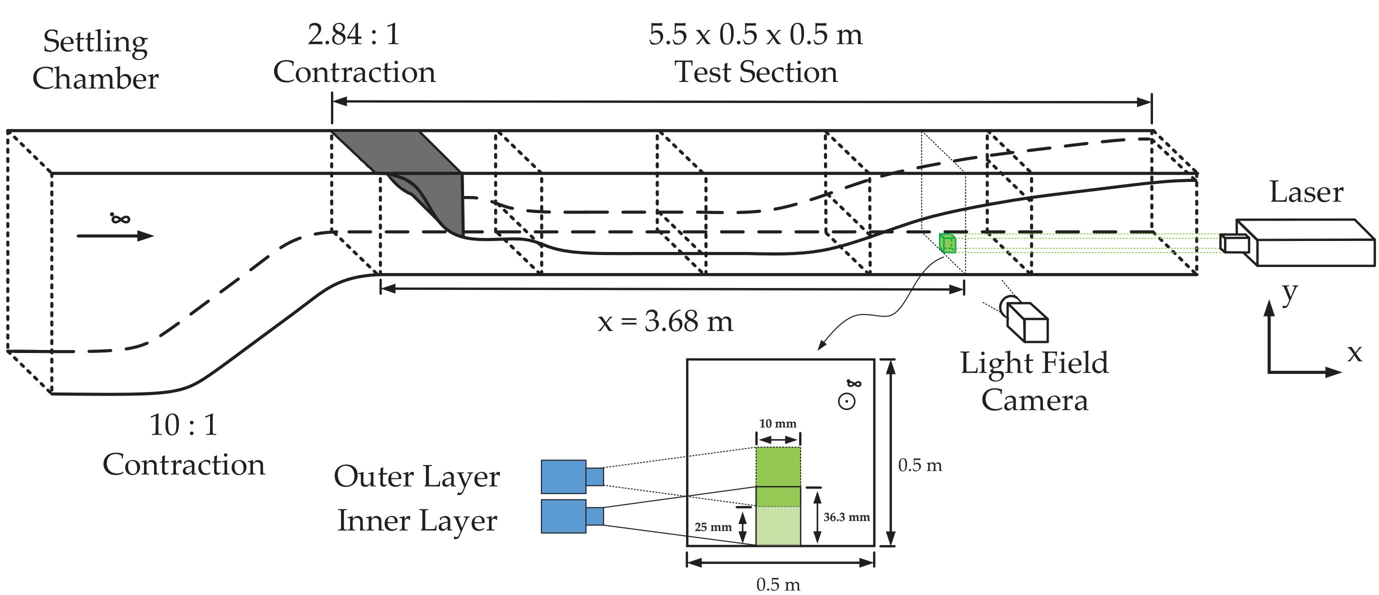


Fig. 1 Schematic of the LTRAC water tunnel and the LF-PIV experimental setup of the inner and outer layer measurements

To achieve the best accuracy, the magnification of light field camera was set to $M = 1$, which did not permit the capture across the whole boundary layer by a single capture. Due to this limit, the measurement was separated into two sections: the inner layer and the outer layer. After the inner layer, the light field camera was moved vertically upwards 25mm to perform the outer layer measurements. 20 independent batches of light-field PIV images were captured for both inner and outer layer measurements, each consisting of 250 instantaneous image pairs.

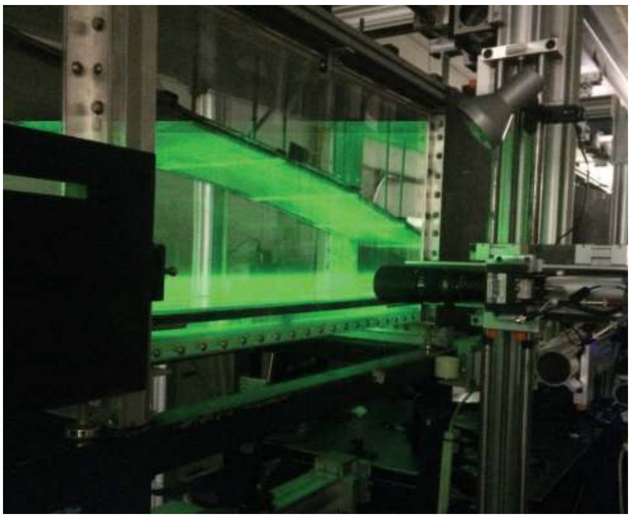
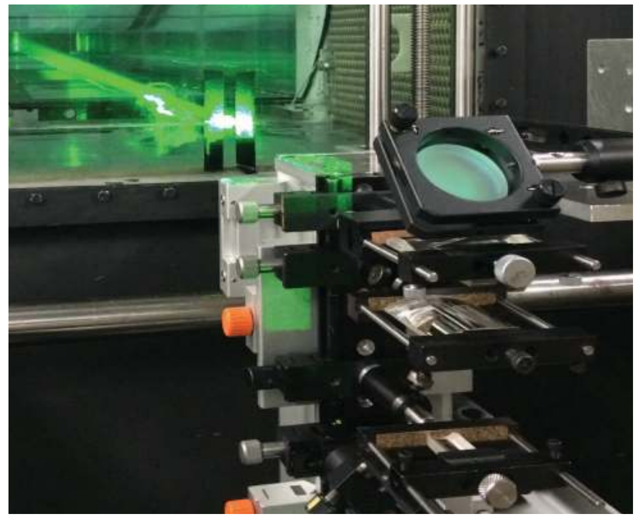



Fig. 2 Experimental setup of APG-TBL measurement with LF-PIV system

3. Data process of Light Field PIV

The light-field particle images were reconstructed by the Dense ray tracing-based MART (DRT-MART) method proposed by Shi et al. (2017), which firstly identifies non-zero voxels using dense ray tracing, then iteratively updates voxel intensity by the MART method (Eq. 1), in a similar fashion to MLOS in Tomo-PIV (Atkinson and Soria, 2009).

$$E(X_j\,,Y_j\,,Z_j)^{k+1} = E(X_j\,,Y_j\,,Z_j)^{k}\left(\frac{I(x_i,y_i)}{\sum_{j\in N_i} w_{i,j}\cdot E(X_j\,,Y_j\,,Z_j)^{k}}\right)^{\mu\cdot w_{i,j}} \quad (1)$$

where $E(X_j\,,Y_j\,,Z_j)$ is the intensity of the j-th voxel; $I(x_i,y_i)$ is the intensity of the i-th pixel, which is known from the captured light-field image; and $w_{i,j}$ is the weighting coefficient, which is the contribution of light intensity from the j-th voxel to the i-th pixel value.

In this experiment, the raw particle images were reconstructed by the DRT-MART method with a pixel voxel ratio of 3:3:10 in x-, y- and z-direction, which results in a reconstruction domain of 733×2200×182 voxels (0.0165×0.0165×0.055$(mm)^3$/voxel) for each image pair. A three dimensional multi-grid cross correlation (Soria 1996) is then used to calculate the raw instantaneous velocity volume with 50% overlap and an initial and final interrogation window size of 256×256×64 and

128×128×32 respectively. The raw velocity volume is then further processed by median filter and linear interpolation to identify and replace any incorrect velocity vectors. Considering the quite huge calculations involved in the reconstruction and cross correlation steps, GPU parallel processing (using 6 GeForce 1080Ti cards) is applied to the to improve the computational efficiency.

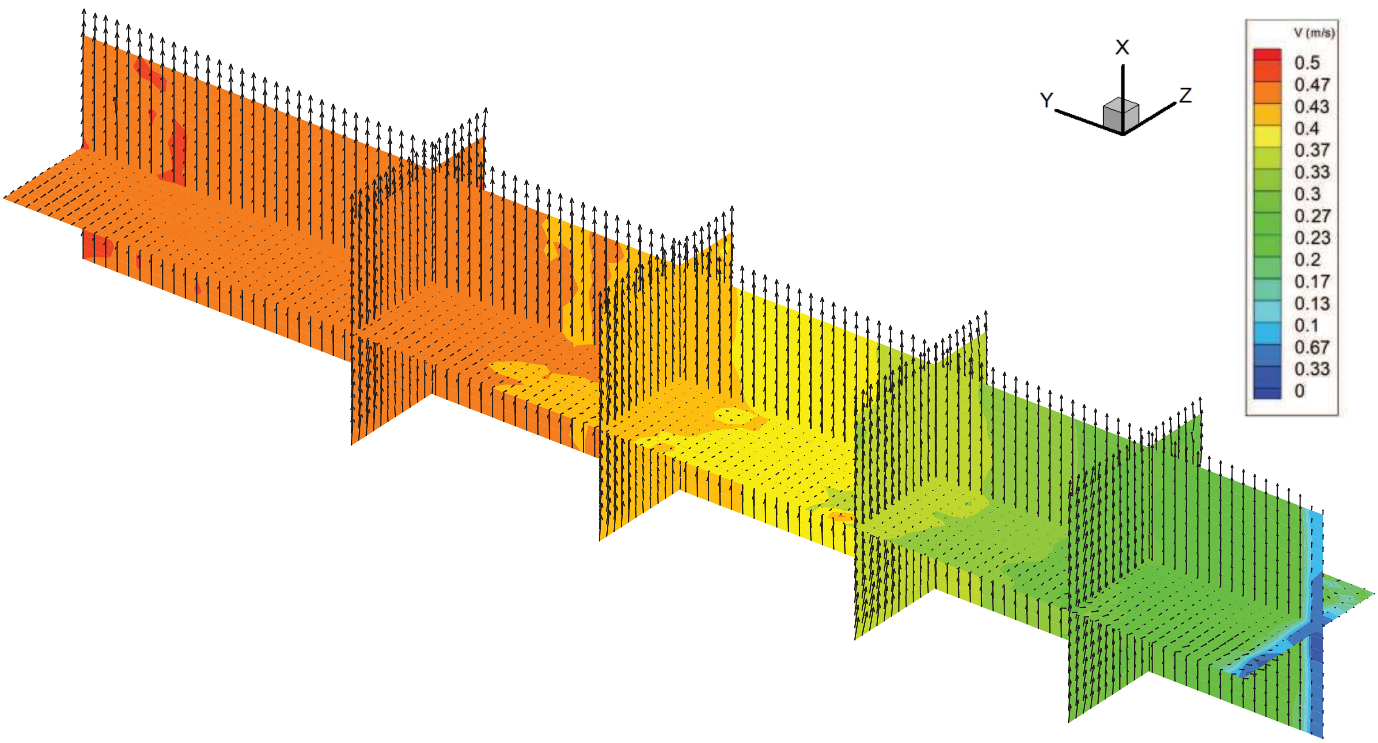


Fig. 3 Overview of averaged volumetric velocity field of APG -TBL measured by LF-PIV and assembled with inner and outer layer data. The outer flow is in the positive x-direction, and the wall lies here on the right-hand side.

4. Velocity Profiles Compared with the 2D-PIV Results

As mentioned before, the aim of this experiment is to find out the resolution of LF-PIV in measurement of turbulent boundary layer. So with 600 of instantaneous velocity fields, the velocity profiled can be calculated out to compare with the 2D-PIV's measurement from a previous measurement campaign in the same facility (Atkinson et al 2016a).

For the Light-Field PIV, the measurement area is actually a small volume. Because the volume is small enough, the XOZ plane with different value of –y location, which is perpendicular to the wall, can be regard as one point in y axis. So averaging the volume data in the streamwise dimension, the statistics in each y-location were calculated from a total of 216600 samples. After that a Gaussian validation method is applied to filter the data in each y-location.

The mean freestream velocity calculated from LF-PIV results is $\sim 466\ \mathrm{mm/s}$, which belongs to the self-similar region according to Atkinson (2016a). The wall-normal profiles of the mean streamwise velocity $\langle u \rangle$ and the two Reynolds stress components $\langle uu \rangle$ and $\langle vv \rangle$ are shown in figure 4. Profiles are compared between LF-PIV and 2D-PIV's results at streamwise location $x = 3.68m$, and all values are normalized by the outer velocity and the displacement thickness δ_1.

From the mean streamwise velocity profile, it is seen that, when $y/\delta_1 > 0.1$, not very close to the wall, the LF-PIV and 2D-PIV results agree generally well, especially the inner test of LF-PIV. And for the outer test of LF-PIV, there is some assemble error due to the difference of magnification factors between the inner and outer test, which is caused by the small displacement of the camera when moving the camera upward to the outer test position after the inner test.

For the Reynolds stress profile, the LF-PIV is able to observe some indication of the inner peak in the $\langle uu \rangle / {U_e}^2$ and $\langle vv \rangle / {U_e}^2$ profile and agree well with the 2D-PIV's result, where the peak location is near to the displacement thickness. Beyond the displacement thickness the LF-PIV lost its accuracy. And for the main freestream part of the outer test, the results of $\langle uu \rangle$ component is not a straight line, which is probably related to erroneous reconstruction by the DRT-MART reconstruction algorithm without taking the lens defects and misalignment between MLA and image sensor into consideration. This will be discussed in the next section. And to show the performance of the LF-PIV at the slices of volume in –z direction, the Reynolds stress profile $\langle uu \rangle / {U_e}^2$ of two slices at different z positions of LF-PIV volume is compared with 2D-PIV in figure 5.

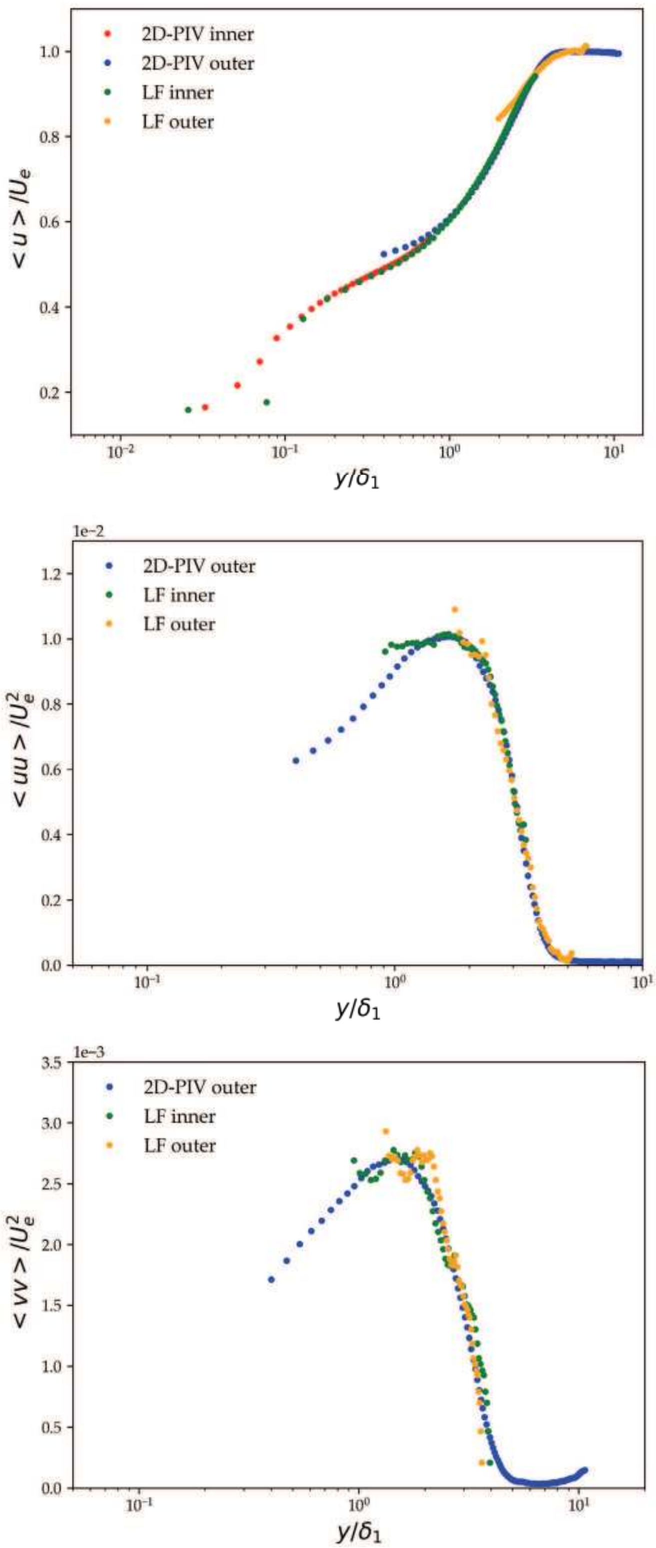
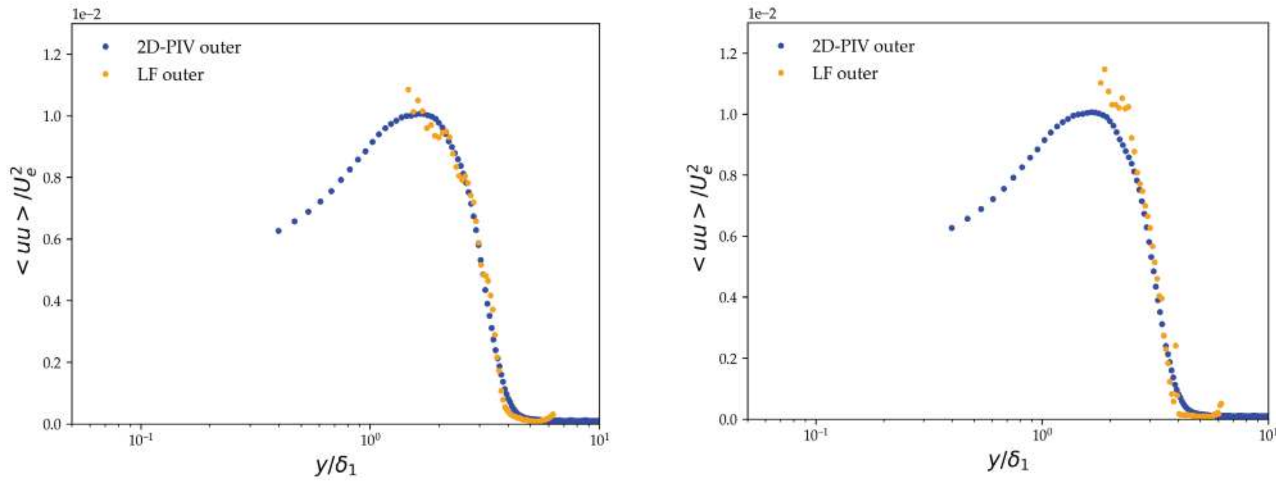


Fig. 4 Mean streamwise velocity profiles and Reynolds stress profiles comparing with 2D-PIV



(a) (b)

Fig. 5 Reynolds stress profile $\langle uu \rangle$ of LF-PIV at different z positions comparing with 2D-PIV. The figure (a) is $z = -1.525mm$ and (b) is $z = -0.696\ mm$, relative to the center of the camera's focal plane ($z = 0\ mm$).

5. Discussion

The results presented in Section 4 show the LF-PIV is able to do the basic measurement of the turbulent boundary layer based on the DRT-MART algorithm. But the performance of LF-PIV in this experiment is far away from its limit. And there is a lot of room for LF-PIV to improve the resolution. Here are two main points. Firstly, the particle density is not optimal (0.5 ppm). Actually, after we finished the experiment in 2016, we found out that the particle density was too low for DRT-MART method to yield optimal reconstruction. Another important point is that the reconstruction algorithm for LF-PIV has improved during the last year. According to Shi and Ding's work (2018), a volumetric calibration method for LF-PIV, which uses the point-like features in light-field particle images to precisely build the relation between voxels and their affected pixels.(Figure 6). By taking lens defects and misalignment between MLA and image sensor into account, this calibration method can get a more accurate weighting coefficient for particle reconstruction than the previous ray tracing method, especially in regions further away from focal plane where the accuracy are significant affected by optical distortions. Figure 6 plots the LF-PIV measurement result for a low speed vortex-ring (Re=2000). It shows that the volumetric calibration could greatly improve the velocity reconstruction quality, especially for regions further away from the camera focal plane. In the next step, the authors plan to perform a series of LF-PIV measurement for APG-TBL using higher seeding density (1ppm) and apply the volumetric calibration for particle reconstruction. It is foreseeable that the measurement resolution will be further improved.

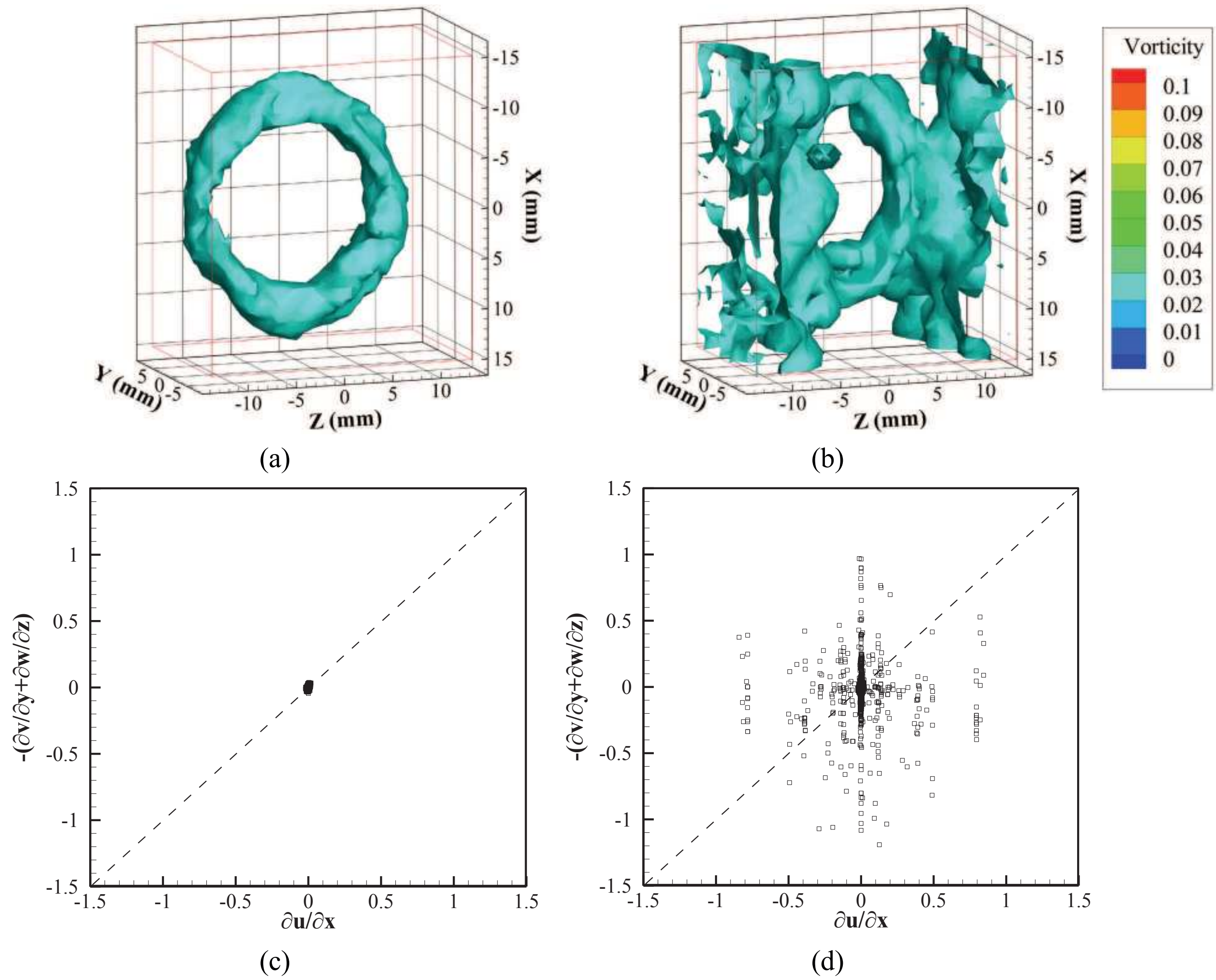


Fig. 6 The vortex-ring LF-PIV experiment results and analysis between volumetric calibration method and ray tracing method. Instantaneous velocity field reconstructed with volumetric calibration (a) and without volumetric calibration (b). Divergence of the instantaneous velocity field reconstructed with volumetric calibration (c) and without volumetric calibration.

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