Experimental study of lid driven cavity flow in the Lagrangian frame of reference

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Summary We study the three-dimensional lid-driven cavity (LDC) flow of different aspect ratios. The study is performed using the three-dimensional particle tracking velocimetry (3D-PTV), allowing for measurements of the flow tracer pathlines along with velocity and acceleration in the Lagrangian frame-of-reference. Our purpose is to learn the three-dimensional structure of laminar and turbulent LDC flows and shed more light on transport and mixing properties of the closed domain physical systems.

INTRODUCTION

Lid-driven cavity (LDC) flow in a rectangular cavity has very well defined boundary and initial conditions, which makes it ideal to study laminar and turbulent flows in closed domains. It became a classical problem in experimental and computational fluid mechanics and over the past decades extensive experimental and numerical studies provided insight into various aspects of the flow structure at different aspect ratios (ratio of the length/width to the depth of the cavity) and Reynolds numbers (typically defined using the lid velocity and the geometry of the cavity). Firstly, lid driven cavity flows were studied in two dimensional (2D) features, and a vast majority performed in the Eulerian viewpoint (in the frame of reference which is fixed in space). Experiments of Kossef & Street [3] altered this picture, clearly demonstrating that the characteristics of this flow are inherently three-dimensional (3D). Three dimensional aspects of turbulent LDC flows became the main topic of interest, and the main progress is thoroughly reviewed in 2000 by Shankar & Deshpande [4]. The review notes, for example that: "*driven cavity flows exhibit almost all phenomena that can possibly occur in incompressible flows ...*". So far, the knowledge about LDC flow characteristics (such as velocity, cavity geometry, Reynolds number dependence, vortices, etc.) and their effects on the transport and mixing properties of passive objects is still limited.
We focus on the Lagrangian aspects of the flows in closed domains, aiming at mixing and transport properties of this physical system. Transport and mixing properties of turbulent flows are of great concern in several applications in nature and engineering and subject of extensive basic and applied research.

EXPERIMENTAL METHOD AND SETUP

Experiments are performed using the apparatus shown in Fig. 1. The flow is confined in a rectangular cavity, filled with water and flow is driven by a moving conveyor belt from the top. The cavity size and ratio can vary by moving the inner glass walls and in the present setup is 200 x 200 x 80 mm (L x H x B, according to Fig. 1). The cavity is equipped with the external walls (all filled with water) to minimize the aberrations due to stereoscopic imaging. Fluorescent (Rhodamine B) particles (mean diameter is 80 μm) are used as the flow tracers. Four CMOS cameras (1280 x 1024 pixels, 10 bit, Mikrotron, Germany) are installed in an angular configuration for the 3D-PTV ([1,3]), and synchronously record images of the seeded particles. The flow is illuminated by Nd: YLF (527 nm, 80 W) pulsed laser (Quantronix, USA). An additional camera is used for the particle image velocimetry (PIV) measurements of the flow in the center plane. The Reynolds number of the presented experiment was 34400 ($Re_B = UB/\nu$, where U = 0.43 m/s is the belt velocity and B = 80 mm is the smallest length of the cavity geometry). The region measured using particle image velocimetry (PIV) in the center plane of the cavity is about 200 x 150 mm and the observation volume of PTV system is roughly 80 x 80 x 40 mm, marked in Fig. 1a.

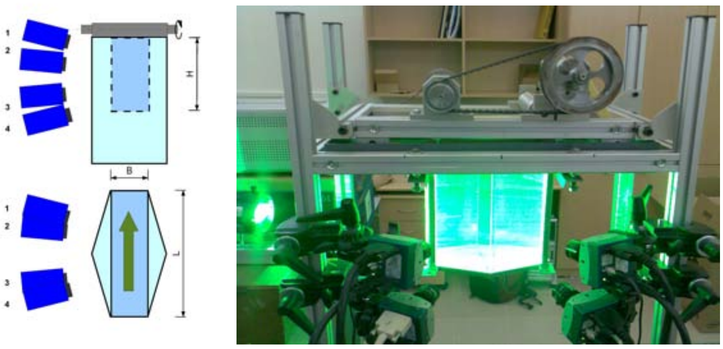

Figure 1: (Left) schematic view of the LDC and 4 camera setup and (right) photo of the setup.

RESULTS AND DISCUSSION

Though the main priority of the present study is essentially the 3D aspects of the flow at different aspect ratios and Reynolds numbers, each run starts with the PIV measurements of the two components (u - horizontal, v- vertical) in the center plane of the cavity. The PIV results (in Eulerian form) will assist as a reference for the qualitative and quantitative comparison with the Lagrangian data obtained with the 3D-PTV. The results shown here are still preliminary.

PIV results: The 2D, two-component ensemble averaged velocity field is shown in Fig.2 (a). Arrows describe the velocity field and color emphasizes the magnitude of the vertical velocity. We can see in the given aspect ratio and Reynolds number, the asymmetrical (in respect to cavity) flow appears as a large circulation with its center shifted towards the right-hand wall. It seems that the strong gradients are close to the right wall of the measured cavity (vorticity shown in Fig. 2d and strain, skipped for the sake of brevity). There is a downward jet with high vertical velocity across the entire depth of the cavity (emphasized by the color in Fig. 2a). More quantitative information is shown in Fig. 2e providing the vertical velocity profile, V(x), emphasizing the difference of vertical velocity across the cavity.

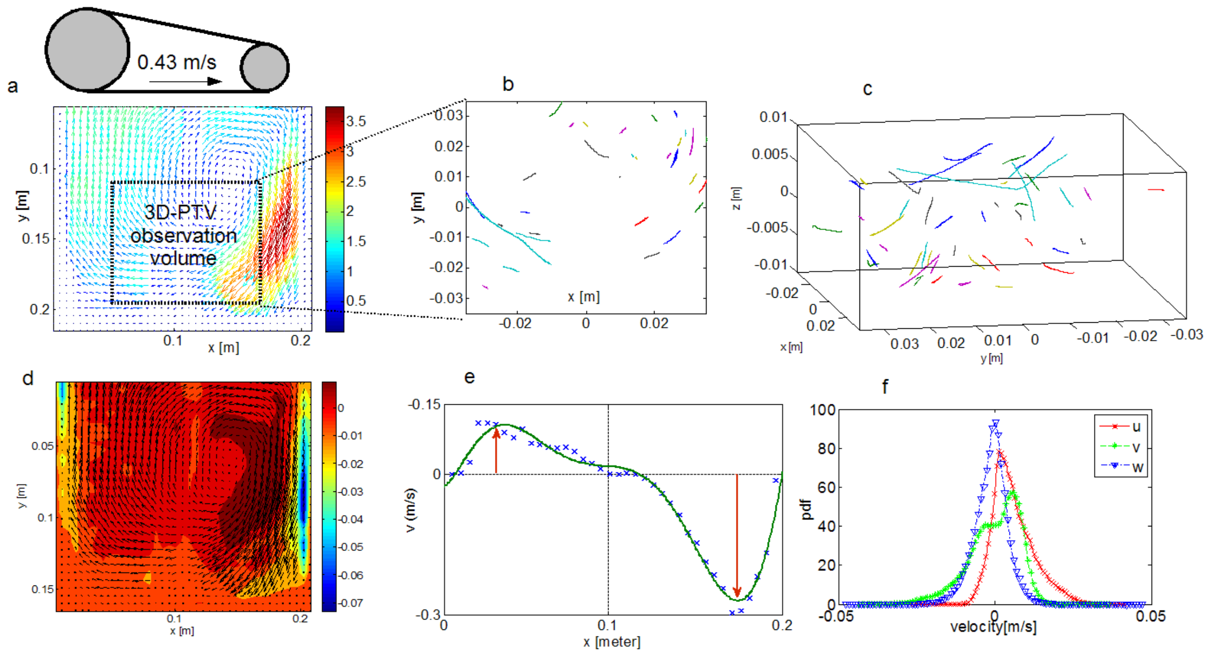

Figure 2: (a) 2D observation of velocity field and velocity magnitude by PIV, (b) 2D projection of the sample of the 3D flow field shown in (c) measured using 3D-PTV Only few trajectories are shown for the sake of clarity. (d) 2D velocity field with color-coded vorticity field, (e) profile of the vertical velocity V(x) and (f) probability density functions of the velocity components: u,v,w.

3D-PTV results: Fig. 2b presents the two-dimensional projection of the 3D data for the sake of visual comparison with the PIV velocity field. Trajectories of single particles show the same structure as in average PIV results in Fig. 2a. It is noteworthy that the result resembles closely the 2D picture when projected on a single plane, but the underlying flow is substantially three-dimensional, as it is shown in Fig. 2c. The 3D view shows clearly that 2D roll is only "projection" of the real picture. Fig. 2f shows the probability density function (PDF) of separate components of fluctuating velocity. PDFs of the different velocity components underline the importance of this study, where significant values of velocity appear in all three directions.

CONCLUSIONS AND FUTURE RESEARCH

This preliminary study uses the regular PIV and 3D-PTV as the experimental tools within the Lagrangian framework. The two experimental systems show similar results in the two-dimensional projection on the centreline plane, but also emphasize the need for the 3D experimental study. A description of the fluid flow in an Eulerian framework using PIV asserts that the most important region in PIV in sense of turbulent production is where the downwards jet impinges on the bottom wall. This is the region where 3D-PTV should be applied to study the various aspects of Lagrangian and three-dimensional nature.

References

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