Lagrangian particle tracking measurements provide new insights into the onset of turbulence in pulsatile particle-laden pipe flow

Lagrangesche Partikelverfolgungs Messungen ermöglichen einen neuen Einblick in das Einsetzen von Turbulenz in pulsierender partikelbeladener Rohrströmungen

Bastian Bäuerlein[1,2,3], Daniel Schanz[4], Andreas Schröder[4,5] and Kerstin Avila[1,2]
1. ForWind - Center for Wind Energy Research, Küpkersweg 70, 26129 Oldenburg, Germany
2. Institute of Physics, University of Oldenburg, Ammerländer Heerstr. 114-118, 26129 Oldenburg, Germany
3. Center of Applied Space Technology and Microgravity (ZARM), University of Bremen, Am Fallturm 2, 28359 Bremen, Germany
4. Department Experimental Methods, Institute of Aerodynamics and Flow Technology, German Aerospace Center (DLR), Göttingen, Germany
5. Brandenburgisch Technische Universität (BTU) Cottbus-Senftenberg, Germany

Lagrangian Particle Tracking, particle-laden flows, pipe flow,
Lagrangesche Partikelverfolgung, partikelbeladene Strömungen, Rohrströmungen

Abstract

Particle suspensions in pulsatile pipe flow are ubiquitous in industrial processes and physiological systems. Of particular interest is the turbulence transition in such flows, where turbulent structures typically arise localized in time and space due to the pulsation. To elucidate the particle-flow interaction, we perform three-dimensional and time-resolved particle tracking with the Shake-The-Box (STB) algorithm in a long pipe experiment (length up to $20\ \mathrm{m}$, with a diameter of $D = 28\ \mathrm{mm}$) and use two types of particles having different diameters ($0.1 - 0.4\ D$). By using hydrogel particles, we can simultaneously obtain the fluid and particle motion, including their rotation. Here we present our recent improvements of the STB-setup, which allows an increase of the field of view, a higher spatial resolution and a minimization of ghost tracks.

Zusammenfassung

Partikelsuspensionen in pulsierender Rohrströmung sind allgegenwärtig in Industrieprozessen und physiologischen Systemen. Von besonderem Interesse ist der Turbulenzübergang in solchen Strömungen. Aufgrund der Pulsation treten turbulente Strukturen typischerweise lokalisiert in Raum und Zeit auf. Um die Interaktionen von Partikeln und Strömung zu untersuchen, setzen wir dreidimensionales und zeitaufgelöstes Partikel-Tracking mit dem Shake-The-Box (STB) Algorithmus ein. In dem langen Rohrexperiment (Länge bis zu $20\ \mathrm{m}$, mit Durchmesser $D = 28\ \mathrm{mm}$) werden zwei Typen von Partikeln mit unterschiedlichen Durchmessern ($0.1 - 0.4\ D$) verwendet. Der Einsatz von Hydrogel Partikeln erlaubt es uns simultan die Bewegung von Fluid und Partikel und auch die Partikelrotation zu erfassen. In dieser Arbeit präsentieren wir unsere aktuellen Verbesserungen des STB-Aufbaus, die ein größeres Sichtfeld, eine höhere räumliche Auflösung, sowie eine Minimierung von Geisterpartikeln ermöglichen.

Introduction

Particle-laden flows are ubiquitous in engineering and nature, ranging from the flow of slurries and sedimentation processes to the cardiovascular blood flow in living organisms. Most of these flows are time dependent, with a pulsatile mass flux as it occurs e.g., in blood flow. Despite the relevance of pulsatile particle-laden flows, little is known about the motion of particles in such flow environments and how they trigger turbulence. In this work we present our experimental setup and show that it is ideally suited to elucidate particle-flow interaction based on Lagrangian particle tracking.

The accuracy of optical flow measurements like Particle Image Velocimetry (PIV) or Lagrangian Particle Tracking (LPT) strongly depends on the quality of the visual access to the fluid flow. This is particularly challenging for particle-laden flows, where particles often block or refract the illumination, thereby creating voids in the camera images. A recent approach for studying suspension flows is based on transparent superabsorbent polymers or hydrogels as particles. By swelling up these materials in aqueous solutions, the refractive index and density can be closely matched to the surrounding working fluid. For PIV or LPT measurements, this makes it possible to capture a particle-laden fluid flow (Zade et al. 2018). This was shown to work with 2D PIV even for high particle concentrations up to 18% of the volume (Zhang and Rival 2018). Additionally, hydrogel with tracers grafted to the interface can be used to track the particle motion and rotation in combination with the fluid flow (Klein et al. 2013). In our previous study we also used hydrogel particles and achieved simultaneous measurements of the fluid velocity and the particle motion in pipe flow, using three-dimensional Lagrangian Particle Tracking (with the Shake-The-Box (STB) algorithm) (Bäuerlein et al. 2022). Here, the attachment of tracers on the hydrogel's surface enabled the determination of the particle trajectory and its rotation. Despite the novelty of this approach there were still some limitations. The remaining refraction of the larger hydrogel spheres ($0.41\ D$) resulted in larger uncertainties or falsely identified ghost tracks in the proximity of the particles.

By extending the measurement setup and procedure to six cameras, this can be greatly reduced. Furthermore, the six-camera setup also enables the measurement with larger concentrations of small polystyrene particles ($0.1\ D$).

In this paper, we will present how we improved our setup and evaluation procedure compared to Bäuerlein et al. (2022). The achieved improvements are illustrated for particle-laden pulsatile pipe flow with both large hydrogel spheres and small polystyrene spheres.

Experimental setup to study pulsatile particle-laden pipe flow

The pipe flow experiment is made of glass with an inner diameter $D = 28\ \mathrm{mm}$ and has a length of up to $20\ \mathrm{m}$ (see Fig. 1). The working fluid is a water-glycerol (up to $20\ \mathrm{wt\%}$) mixture to match the density of either large hydrogel spheres with a particle diameter ($D_p \cong 11.5\ \mathrm{mm} = 0.41\ D$) or small polystyrene particles ($D_p = 2{,}8\ \mathrm{mm} = 0.1\ D$). The particles are seeded into the fluid at a large inlet reservoir (see Fig. 1 ii) with volume concentrations up to $\phi = 1\%$.

Through a trumpet shaped entrance nozzle, the particle-laden flow enters the pipe consisting of multiple borosilicate glass segments mounted to an aluminum strut structure (i). To artificially perturb the flow, individual segments can be exchanged with, for example, a bending in the pipe geometry. The flow is created by pulling fluid with a large hydraulic piston (iv) driven by a linear actuator (v) with a servo motor (vi). To create a pulsatile flow, an oscillation is modulated on top of the mean servo speed. Frequency, amplitude, and mean velocity of the pulsatile flow can be freely adjusted. The corresponding dimensionless parameters are the Reynolds number $Re = U\ D/\nu$ (with the mean flow velocity U and the kinematic viscosity ν), the Womersley numbers $Wo = 0.5\ D\sqrt{2\pi\ f/\nu}$ as the nondimensionalized pulsation frequency f and the amplitude $A = \hat{U}/U - 1$ (as the ratio between peak velocity $\hat{U}$ and mean velocity U). The piston is connected to the pipe through a second reservoir (iii) at the end of the pipe, where the particles are separated via a mesh filter.

For multiphase flow measurements, we introduce two different types of particles into the flow. First, as described in Bäuerlein et al. (2022), large hydrogel particles are used to simultaneously measure the fluid flow and particle motion. These start as small $1.9\,\mathrm{mm}$ polyacrylate particles and swell up to their final size of $D_p \cong 11.5\,\mathrm{mm}$ when exposed to water. Due to the polymer content, the swollen hydrogel particles are slightly heavier than water ($\sim 1.01\,\mathrm{g/cm^3}$). To achieve the neutral buoyance the particles are seeded into a water glycerol mixture (up to $1.05\,\mathrm{g/cm^3}$) of the pipe flow. As they absorb the water-glycerol, they increase in weight and become neutrally buoyant for about three hours. For the smaller polystyrene particle ($D_p = 2.8\,\mathrm{mm}$) used in this study, the procedure is simpler. The glycerol fraction in the water can be directly adjusted to match to density of the fluid to the polystyrene ($1.05\,\mathrm{g/cm^3}$). Unlike hydrogel the buoyancy of the polystyrene particles is not limited in time, and will only be affected by temperature changes in the working fluid.

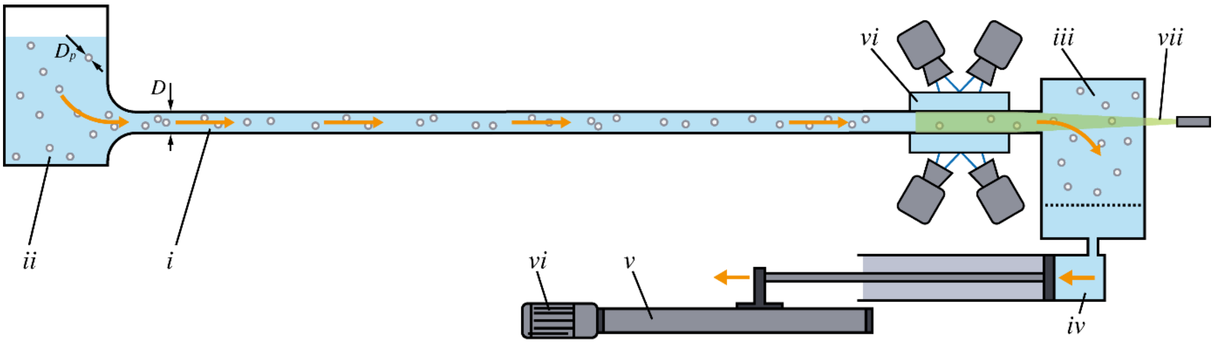

Fig. 1: Sketch of the pipe flow experiment. The suspension flows from an inlet tank (ii) into the glass pipe (i), passes a STB-measurement volume (vi) and ends in an outlet tank (iii). The large particles are collected in this tank, while the fluid is pulled through a mesh into the piston (iv), driven by linear actuator (v) with a servo motor (vi). A laser illumination (viii) is provided axially through the outlet tank.

Shake-The-Box measurements

The measurement equipment for STB is located at the end of the pipe (see Fig. 1). The setup consists of four high speed cameras (type VEO 640L from Phantom $1.4\,\mathrm{kHz}$ @ $2560 \times 1600\,\mathrm{Px}$), a pulsed laser illumination (using a pulsed dual-cavity Nd:YAG laser, $2 \times 50\,\mathrm{mj}$ @ $1\,\mathrm{kHz}$, type DM50-527-DH from Photonics), a refractive index matching prism, and the processing software Davis 10 from LaVision.

The main component to enable measurements in the round pipe, is the refractive index matching prism to compensate the optical distortion from the pipe wall. A hexagonal prism is made from acrylic glass and placed around the observed pipe segment. To match the refractive index of the borosilicate glass pipe wall, the prism is filled with the working fluid. Due to the required density matching with the particles, the working fluid is not completely index matched to the glass, resulting in some small remaining distortion. The cameras can be positioned in a radial plane around the prism, with each camera view facing the measurement volume through one of the prism's surfaces.

One of the main difficulties in 3D Lagrangian Particle Tracking is to avoid falsely identifying and tracking of particles, or so-called ghost particles. In our setup, these ghosts can arise from remaining distortions in the optical path of the cameras. One source of distortions is the slight refractive index differences between the glass of the pipe and the working fluid. This effect can be mitigated by a finely resolved volume self-calibration procedure (Wieneke 2008) with up to

GALA e.V., Karlsruhe, Germany, ISBN 978-3-9816764-9-5

20×20 sub-volumes over the cross section of the pipe. A second source of optical distortion can arise from refractions caused by the large hydrogel particles. As the particles move through the measurement volume, their refractions cannot be compensated in a calibration procedure. Therefore, the STB algorithm will regularly identify ghost particles for both the interface of the hydrogel and in the surroundings regions of the flow, where one or multiple camera views are slightly distorted. In the previous study these ghost tracks had to be removed in post-processing. As they usually do not match the true trajectories in magnitude or directions, a spatial median filter or velocity thresholding can be used. However, if larger quantities of ghosts appear, due to an increased accumulation of tracers or some imperfections on the hydrogel interface, this can become more challenging.

(a) (b)

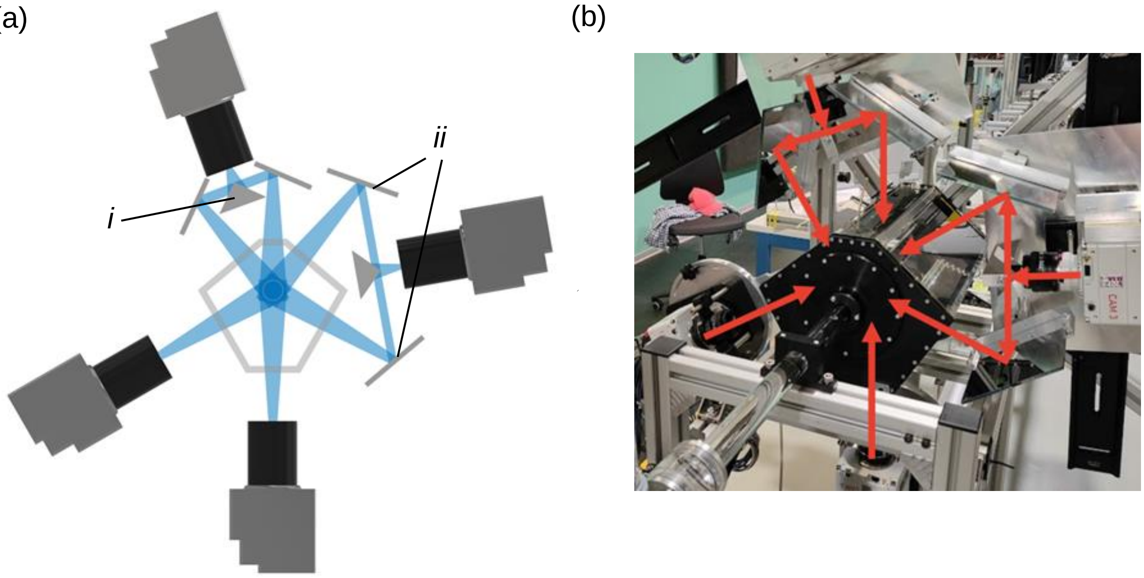

Fig. 2: STB-setup with six viewing angles and four cameras. In the sketch in (a) the view splitting of two of the cameras with the splitting mirror prism in front of the lens (i) and two tilted mirrors (ii) directing the view into the refractive index matching box. The same setup is shown in (b) as a photograph, with the red arrows indicating the optical path of each camera.

The number of ghost tracks in three-dimensional measurement methods is most efficiently reduced by increasing the number of independent camera angles (Discetti and Astarita 2014). As each tracer is triangulated from all the cameras views, the chance of a coincidental misidentification becomes more unlikely. In our setup, the refractive index matching prism has a hexagonal cross section, allowing for easy incorporation of six views, compared to the original four. Furthermore, since the field of view of the measurements is rather long and narrow (at least $4D$ in length), compared to the aspect ratio of the camera sensors (4×3), a single camera can be used to capture multiple viewing angles.

The optical setup is shown in Fig. 2. For two of the cameras, a mirror prism is positioned directly of front of the lens, splitting the view by $90°$ into two directions. A second set of tilted mirrors directs the view through the refractive index matching prism towards the pipe. Care must be taken to ensure that each view is directly orthogonal to the surface of the prism and the magnification of each view is the same. To achieve this, the split cameras are positioned on the bisecting angles between two prism surfaces, and the distance of the cameras is selected so that optical path length is the same in all six views. After aligning all cameras and mirrors, they are securely fixed in their orientation to prevent shifts during measurements that could necessitate recalibration or render recordings unusable. It is worth noticing that in the selected configuration, two of the views (from the top and bottom) are directly $180°$ apart. While this is usually not advisable as both views will show the same tracer pattern, making them redundant, in our setup, the remaining refractions, especially from the hydrogel, result in different projected

GALA e.V., Karlsruhe, Germany, ISBN 978-3-9816764-9-5

tracers in both views, providing additional information to avoid ghost tracks. The updated camera configuration also results in a new minimum distance of the camera and minimum axial length of the investigated pipe section of $\geq 6\,D$.

The second modification to the setup is for the laser illumination. For the STB measurements, it is optimal to fully illuminate the entire cross section of the pipe without any light shining onto the walls, to avoid reflections. In the previous setup, the laser was expanded with a telescope lens resulting in a slightly divergent beam. This configuration, in combination with the Gaussian light intensity profile of the laser, led to tracers close to the wall receiving little or no light compared to the centerline of the pipe. To improve on this, the beam is first expanded to a diameter larger than the pipe and then collimated with a second lens (see Fig. 3). An iris aperture is used mask the beam making it round and precisely matching the inner diameter of the pipe. This also effectively avoids using the lower intensity region of the laser intensity profile.

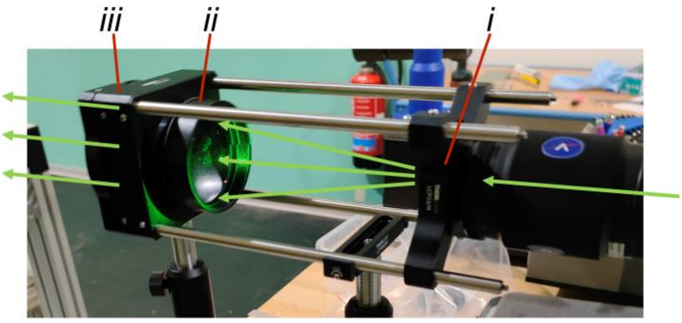

Fig. 3: Laser optics for collimated illumination of the pipe. A telescope lens (i) expands the beam, and a second convex lens (ii) is used for a collimated laser beam. An iris aperture (iii) mask the light to the diameter of the pipe.

The calibration procedure, employing a custom calibration plate and volume-self calibration, as well as the processing with the Shake-The-Box algorithm (Schanz et al. 2016) and post-processing steps in LaVisions Davis 10, remain largely unchanged by the optimization of the setup (see Bäuerlein et al. (2022)).

Particle-laden flow with hydrogel particles

The main goal of this study was to achieve an improved resolution and reduce the number of erroneous tracks, especially when large hydrogel particles are added to the flow. An example of the new measurements in the vicinity of a hydrogel particle is shown in Fig. 4(a). Comparing this to the previous measurements in (b), we can already observe a significant reduction of ghost tracks, which are indicated by the sporadic large velocity tracks in white. Minimizing ghost tracks is not only important for accurately determining the particle motion but also essential for the Eulerian velocity field reconstruction with the VIC# method. While a human observer is very trained in ignoring small outliers, the reconstruction considers all trajectories equally, and a few errors can lead to significant deviations.

In addition to the observed reduction of ghost tracks, the new experiments allowed a larger measurement domain with an axial length of $6\,D$. In addition, the number of tracked tracers could be improved from ~ 3000 tracks in the volume to around 10000 tracks by increasing the image density of tracers. As demonstrated in the previous study, the presence of large hydrogel particles can induce turbulent structures in both the upstream and downstream wake. A longer measurement volume and more tracked tracers are therefore highly beneficial to elucidate the particle-flow interactions. More details on these dynamics will be provided in the final section.

GALA e.V., Karlsruhe, Germany, ISBN 978-3-9816764-9-5

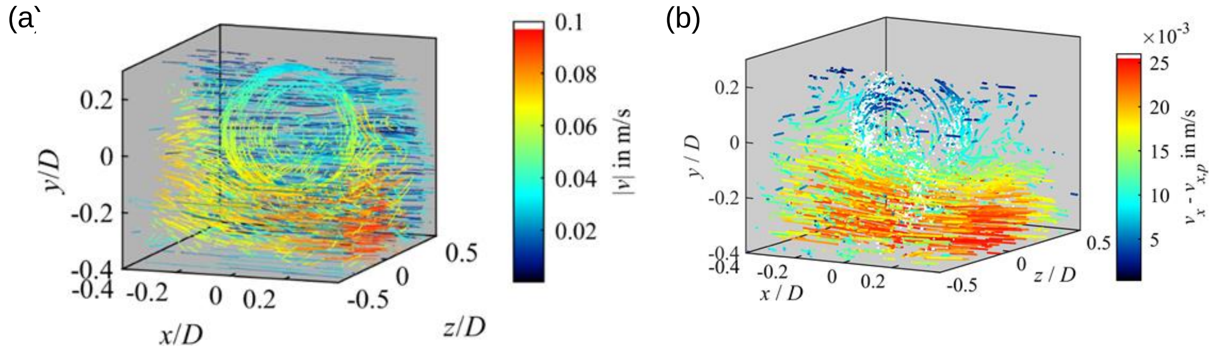

Fig. 4: (a) Example of the Lagrangian tracer trajectories in the vicinity of a large hydrogel particle, calculated with the new measurement method. Compared to previous measurements (b) (taken from Bäuerlein et al. (2022)) the number of ghost tracks is drastically reduced.

Particle-laden flow with polystyrene particles

The large hydrogel particles can provide valuable information about the particle trajectory and its rotation for single particles. However, studies investigating the turbulence transition in particle-laden steady have shown that the transition depends also on the particle diameter (Matas et al. 2003, Hogendoorn et al. 2022) and the particles used were hard. To be able to directly compare to these studies, we use transparent polystyrene particles ($D_p = 2{,}8\ \mathrm{mm} = 0.1\ D$) as a second type of particles (see Fig. 5). Unlike the hydrogel particles, density matching of the polystyrene particles is relatively straightforward by adjusting the glycerol mass fraction in the water. However, one disadvantage of the polystyrene particles is that they are not refractive index matched to the fluid. While the transparency allows some of the laser illumination to pass through the particles, they still produce reflections, as shown in Fig. 5(b). This forces us to limit the maximum laser intensity to prevent strong reflections and thus damaging the cameras. Furthermore, as the laser beam passes through $\sim 1\ \mathrm{m}$ of particle-laden flow before reaching the measurement field of view, increasing the particle concentration leads to more of the light being reflected, thereby reducing and unevenly distributing the illumination for the measurements. This limits the particle concentration to approximately $\phi \leq 1\%$. Despite the reduced laser light, a sufficient tracer light intensity can still be achieved due to the strong gain from the $50\ \mu\mathrm{m}$ polyamid tracers.

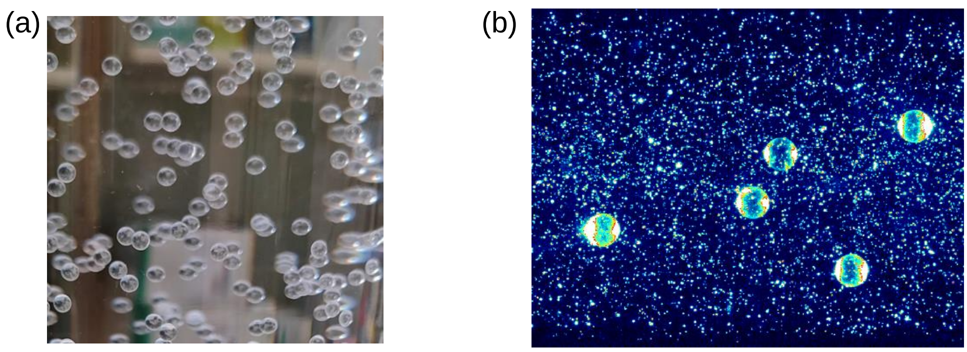

Fig. 5: Small transparent polystyrene particles in a beaker as seen by naked eye (a) and in the pipe flow experiment visualized by the camera images under laser illumination (b).

For STB processing of the measurements with polystyrene particles, the two additional camera angles prove to be similarly advantageous as for the hydrogel. Specifically at the reflective front of the polystyrene particles the amount of ghost tracks is significantly reduced. A calculated trajectory field in pulsatile particle-laden flow is shown in Fig. 6(b). However, since refractive index matching or interface tracers are not present for the smaller particles, determining their motion is not as straightforward as with the hydrogel particles. Additionally, the inhomogeneous and reduced illumination causes a loss of about $\sim 30\%$ in the average number of obtained tracks compared to the measurements with the hydrogel. Despite these limitations, a qualitative understanding of the particle-laden fluid flow can still be obtained. To further improve the method, the existing volume calibration could also be employed in a second Lagrangian Particle Tracking operation to track the large polystyrene spheres.

Turbulence for different particle perturbations in pulsatile flow

To demonstrate the capabilities of the presented STB measurement method an example of particle-laden pulsatile flow with $Re = 1277$ and $Wo = 8$ is shown in Fig. 6 with the perturbation of a single large hydrogel particle in (a), compared to multiple smaller polystyrene particles in (b). With the large particle perturbation, initially only the upstream flow is turbulent. As flow decelerates the formation of vortices in the downstream front of particle leads to secondary turbulence patch. In the case of a suspension with smaller polystyrene particles the emerging turbulence in no longer spatially localized as the globally distributed particles perturb the flow in the entire volume. Future investigations with this method will shed light on how particles of different sizes trigger turbulence and allow for comparisons with other types of flow perturbations.

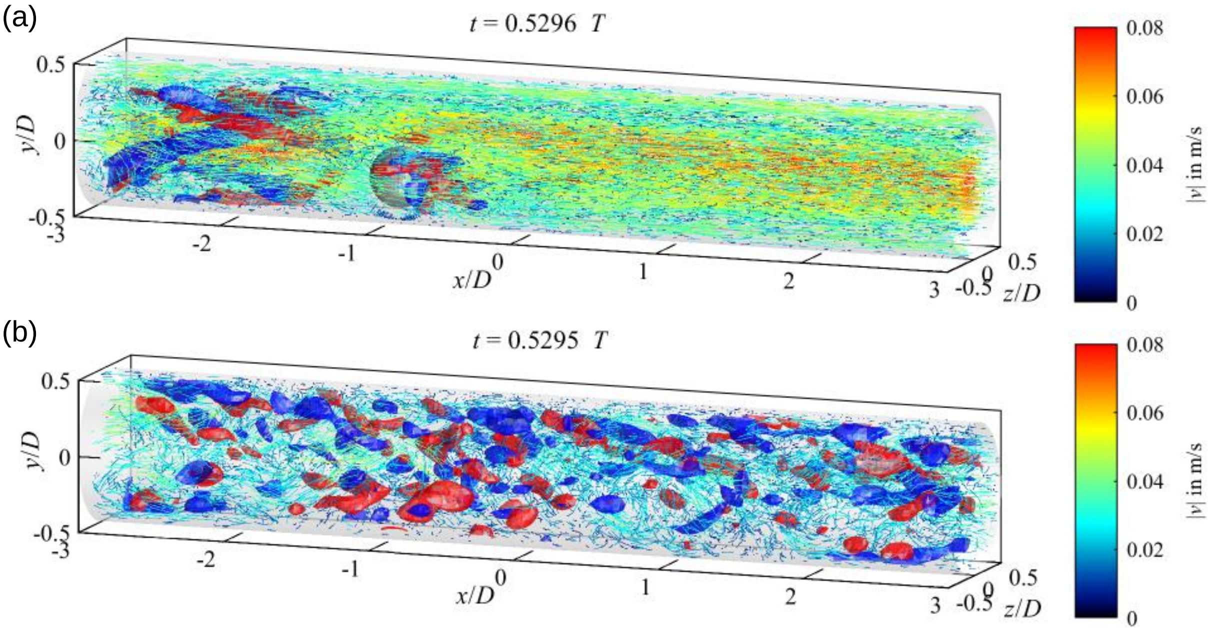

Fig. 6: Snapshot of the flow field with the onset of turbuelnce from Shake-The-Box measurements in a pulsatile pipe flow $Re = 1277, Wo = 8$. The red/blue surfaces correspond to the streamwise vorticity with $\omega_x = \pm 10\ 1/s$. (a) The flow contains a large hydrogel particle ($D_p = 0.41\ D$), indicated by the grey sphere. (b) The flow contains multiple smaller polystyrene particles ($D_p = 0.1\ D$), at a concentration of $\phi \approx 1\%$.

Conclusion

In this paper we present the improvements of our Shake-The-Box measurements of particle-laden pipe flow compared to Bäuerlein et al. 2022. We increase the number of camera views from four to six and employ a collimated laser illumination. Both modifications largely reduced the number of ghost tracks and allowed an increase of the measurement volume along the pipe from 4 to 6 pipe diameter D. In addition, the spatial resolution could be significantly improved due to more identified tracer tracks. Measurements with polystyrene particles became doable with this setup. In the measurements with hydrogel particles the uncertainty of

GALA e.V., Karlsruhe, Germany, ISBN 978-3-9816764-9-5

determining the particle motion and rotation could be reduced. Overall, the particle-fluid interaction in pipe flow can be obtained with this setup in an unmatched manner.

Acknowledgements

This work was funded by the Deutsche Forschungsgemeinschaft (DFG, German Science Foundation) in the framework of the research unit FOR 2688 ‘Instabilities, Bifurcations and Migration in Pulsatile Flows’ under Grant No. AV 156/1-1, and INST 144/464 for the STB-system.

Literature

Bäuerlein, B., Schanz, D., Schröder, A. and Avila, K., 2022: "Lagrangian particle tracking and measurements of particle rotation elucidate dynamics of pulsatile particle-laden pipe flow", 29. Fachtagung Lasermethoden in der Strömungsmesstechnik, Deutsche Gesellschaft für Laser-Anemometrie GALA e.V., Ilmenau, Germany

Disecetti, S. and Astarita, T., 2014: "The detrimental effect of increasing the number of cameras on self-calibration for tomographic PIV", Measurement Science and Technology, 25, 084001

Hogendoorn, W., Chandra, B. and Poelma, C., 2022: "Onset of turbulence in particle-laden pipe flows", Physical Review Letters, 7(4), L042301

Klein, S., Gibert, M., Bérut, A. and Bodenschatz, E., 2013: "Simultaneous 3D measurement of the translation and rotation of finite-size particles and the flow field in a fully developed turbulent water flow", Measurement Science and Technology, 24(2),

Matas, J. P., Morris, J. F., and Guazzelli, E. 2003: "Transition to Turbulence in Particulate1589 Pipe Flow", Physical Review Letters, 90(1), 4,

Schanz, D., Gesemann, S. and Schröder, A., 2016: "Shake-The-Box: Lagrangian particle tracking at high particle image densities", Experiments in Fluids, 57(5), 1-27

Wieneke, B., 2008: "Volume self-calibration for 3D particle image velocimetry", Experiments in Fluids, 45(4), 549-556

Zade, S., Costa, P., Fornari, W., Lundell, F. and Brandt, L., 2018: "Experimental investigation of turbulent suspensions of spherical particles in a square duct", Journal of Fluid Mechanics, 857, 748-783

Zhang, K. and Rival, D. E., 2018: "Experimental study of turbulence decay in dense suspensions using index-matched hydrogel particles", Physics of Fluids, 30(7),