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Three-dimensional particle tracking in pipe flows from distorted images

Dreidimensionale Partikelverfolgung in Rohrströmungen basierend auf verzerrten Bildaufnahmen

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Particle-laden flows, pipe flow, particle tracking,
Parikelströmungen, Rohrströmungen, Partikel-Tracking

Abstract

In pipes with a circular cross-section the tracking of particle motions is challenging due to optical distortions at the pipe wall. A common procedure to minimize these effects is to encase the pipe in a rectangular tank filled with an index matching liquid. However, this approach is costly and time-consuming, especially when measurements at various axial positions of the pipe are required. We developed a method to determine the three-dimensional position of spherical particles in pipe flow without an index-matching device and by using a single camera. The key feature of the method is a virtual reconstruction of the refraction from the curved pipe wall, which allows the determination of true particle positions from a distorted image. The applied image processing and transformation are explained in detail and first results of particle sorting in pipe flow obtained with this method are presented.

Zusammenfassung

Das Verfolgen von Partikelbewegung in Rohren mit rundem Querschnitt ist aufgrund der optischen Verzerrungen an der Rohrwand einer Herausforderung. Eine übliche Methode um diese Effekte zu minimieren ist das Einhausen des Rohres mit einer rechteckigen Box, die mit einer an den optischen Brechungsindex angepassten Flüssigkeit gefüllt ist. Dieser Ansatz ist jedoch aufwendig und zeitintensiv, besonders wenn Messungen an unterschiedlichen axialen Positionen des Rohres benötigt werden. Wir haben eine Methode entwickelt um die dreidimensionale Position kugelförmiger Partikel in einer Rohrströmung zu bestimmen, unter Verwendung einer einzigen Kamera und ohne Brechungsindexanpassung. Hauptmerkmal der Methode ist die virtuelle Rekonstruktion der Brechung des Lichtstrahls an der gekrümmten Rohrwand, was es ermöglicht die richtigen Partikelpositionen aus verzerrten Bildaufnahmen zu bestimmen. Die verwendete Bildverarbeitung und Transformation sind im Detail erklärt und erste Ergebnisse von Partikelanordnungen in einer Rohrströmung werden gezeigt.

Introduction

Wall-bounded particle-laden flows are ubiquitous in many industrial or medical systems and are governed by the interactions between particles, fluid flow and the walls. One of the most well-known inertial effects is the Segre-Silberberg focusing of particles in pipe flow (see Segre and Silberberg 1961), where neutrally buoyant hard spheres migrate towards a stable radial position. At the equilibrium annulus, lift forces due to the shear flow are exactly balanced with the forces from the walls (see Zhang et al. 2016). The time scales of the migration are surprisingly long, so that the pipe has to be of sufficient length to observe the intrinsic particle focusing (see Morita et al. 2017). In addition to the radial migration, an ordering in the axial direction ("trains of particles") can occur (Matas et al. 2004a). For our studies we require an effective imaging method to evaluate the radial migrations and the axial patterns of the particles at the same time.

One of the key challenges for our optical measurements is the light refraction at the curved pipe wall, which strongly distorts the view into the system. This usually hinders accurate measurements of flow characteristics. The conventional method to compensate for this distortion is refractive index matching. Here the circular pipe is placed in a rectangular box, filled with an index matched fluid. Although this method minimizes the effects of refraction it is costly and time-consuming to change the measurement position along the pipe. To record the radial focusing of particles in a pipe flow, usually only a narrow cross-section is illuminated with a light sheet. Particles are located as a they pass the light sheet and cause a reflection detected by cameras with refractive index matching or axial viewpoint (Matas et al. 2004b, Morita et al. 2017). The axial ordering on the other hand is obtained from a camera with a radial direction of view (Matas et al. 2004a). A simultaneous measurement of the radial and axial particle motion has so far not been accomplished without an index matching device. Our method provides both quantities and allows the tracking of the particles for several pipe diameters.

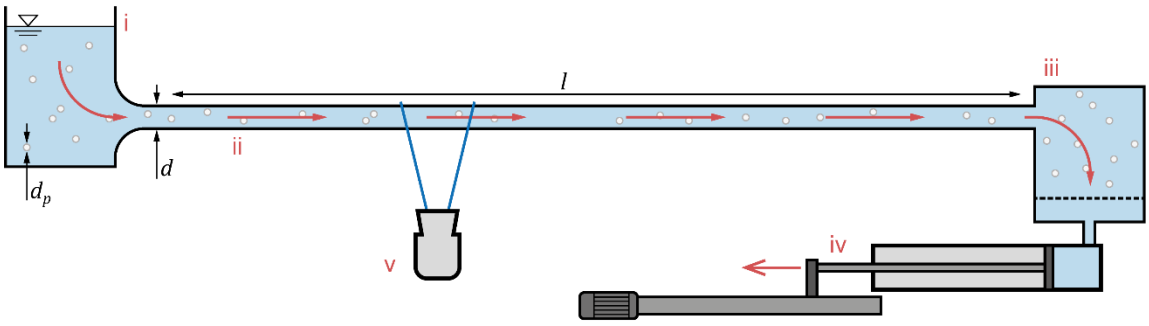

Fig. 1: Schematic of the experimental pipe-flow setup, with the entrance reservoir (i), the measuring section (ii), the outlet container (iii), the driving system (iv) and the camera for particle measurements placed along the pipe (v). The pipe diameter and length are $d = 28\,\mathrm{mm}$ and $l = 20\,\mathrm{m}$, respectively. The diameter of the particles is $d_p \cong 5.9\,\mathrm{mm}$.

Experimental setup

The pipe-flow experiment consists of a borosilicate glass pipe (with an inner diameter $d = 28\,\mathrm{mm}$) through which the fluid is driven by a piston in a pulling motion. The pipe is made of individual segments with a maximum length of $l = 20\,\mathrm{m}$ (corresponding to $714\,d$). The pipe inlet is connected to an open tank and the outlet to a closed tank from which the fluid (without particles) is sucked into the piston. The piston itself is connected to a linear actuator with a servo motor to precisely control the mass flux. The working fluid is distilled water mixed with a

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$10.7\ \%$ mass fraction of glycerol to match the density of the polymer particles (with a diameter of approximately $d_p \cong 5.9\ \mathrm{mm}$).
For the recording of the particle motion a single USB monochrome camera (type DMK 33UP5000 from The Imaging Source, to $2592 \times 2048\ \mathrm{px}$) is used and located as shown in Fig. 1. In the axial direction the field of view has a length of $\sim 140\ \mathrm{mm}$ ($5d$). The recording rate (typically $4\ \mathrm{Hz}$.) is adapted to the maximum expected particle velocity, so that every particle passing the camera is captured at least once. Currently we are interested in the statistics and not in the dynamics of particle clusters, so the recording rate is kept low to reduce the data size and processing time. Beneath the observed pipe section is a mirror placed in an angle, so that the camera captures the particle position from two orthogonal independent views (see Fig. 2). From the two views the three-dimensional particle positions can be computed. Behind the camera is a LED light positioned to illuminate the particles. Since the light is also reflected in the mirror, the individual particles are evenly illuminated in both views. A key advantage of this optical measurement setup is its simplicity, as it only requires a single camera, a mirror and a light source and can be easily moved along the pipe.

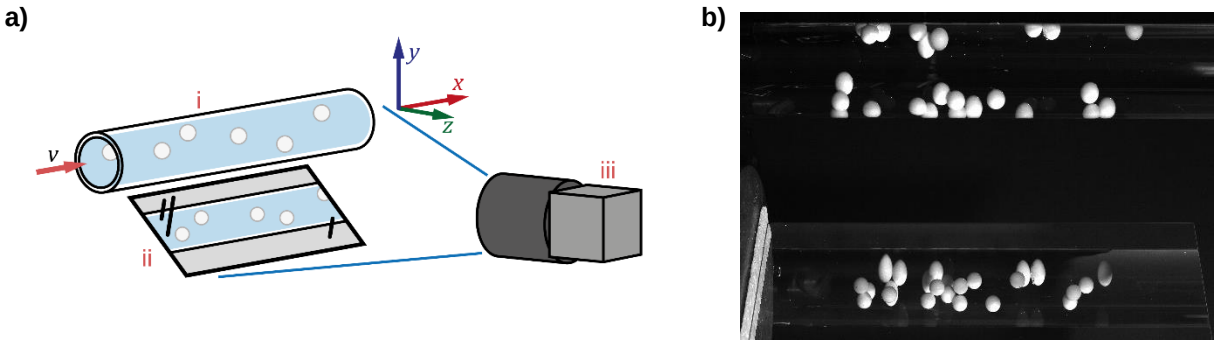

Fig. 2: a) Sketch of a pipe section with the particle-laden flow (i), with the mirror underneath (ii) and the camera from the side (iii) recording both views. b) Snapshot displaying particle clusters from the direct view (upper cluster in the image) and underneath from the mirrored bottom view (lower cluster in the image).

Image preprocessing

In the first step the raw image is cropped into the two views – directly into the pipe and through the mirror. The visible outside wall of the pipe sets the position of the cropping and is used to scale the image (for each view separately, see Fig. 3a). The goal of the consecutive preprocessing is to clearly separate the particles from the background (see Fig. 3b). A Gaussian filter is used to smooth out small imperfections or dust particles in the image. The larger artifacts like reflections on the pipe wall or glare points on the particles themselves are removed via their morphology. A morphology opening is used together with a large structure Top-hat transformation to obtain rather homogeneous images of the particles.
From the preprocessed image the particles can be separated from the background by applying a brightness thresholding. The main difficulty afterwards is to identify all the individual particles despite their partial overlap in the image. For particles with a slight overlap a Watershed transformation is used. Particles with a strong overlap (as the orange particle in Fig. 3c) can only be detected in one of the views, which limits the method to low particle concentrations. As a last filter, particles are required to have a minimum size to remove remaining artifacts, partially visible particles (entering or leaving the field of view) or errors from the Watershed transformation (see Fig. 3c). For each particle the geometric center is computed and from now on used as the detected particle position in the corresponding view. The geometric center is robust against distortion and allows a sub-pixel positioning accuracy.

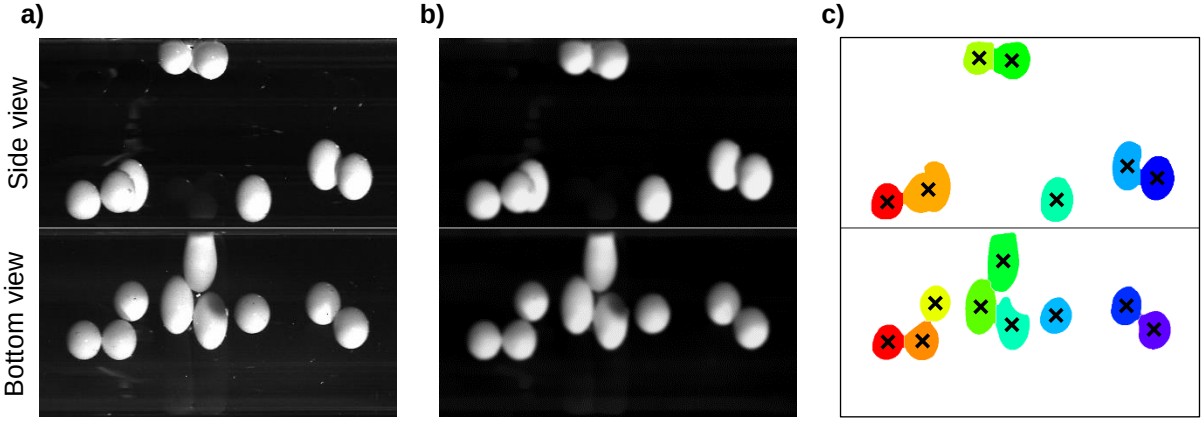

Fig. 3: Preprocessing of the images from both views. a) The cropped raw image corresponding in height to the diameter of the outer wall of the pipe. b) The image after background subtraction and removal of reflections. c) The binarized image with individual particles identified as indicated by different colors. Even though many of the particle slightly overlap in the raw image they can be clearly separated in the analysis. The 'x' symbols mark the identified geometric center and location of each particle in the image.

Reconstructing the image distortion

In the previous step the particles were located as the pixel coordinates in the images. To get the true positions inside the pipe, the pixel coordinates must to be transformed to a three-dimensional coordinate system. This transformation is the key challenge when not using refractive index matching, as the nonuniform refraction along the radial direction makes it impossible to simply undistort the image as a whole, with the aid of checkerboard patterns or calibration plates. The distortion of the particle images depends on the particle position as it is illustrated in Fig. 4. Particles near the wall viewed by the camera appear for example rather circular, whereas the ones on the opposite side of the pipe appear elongated along one axis.

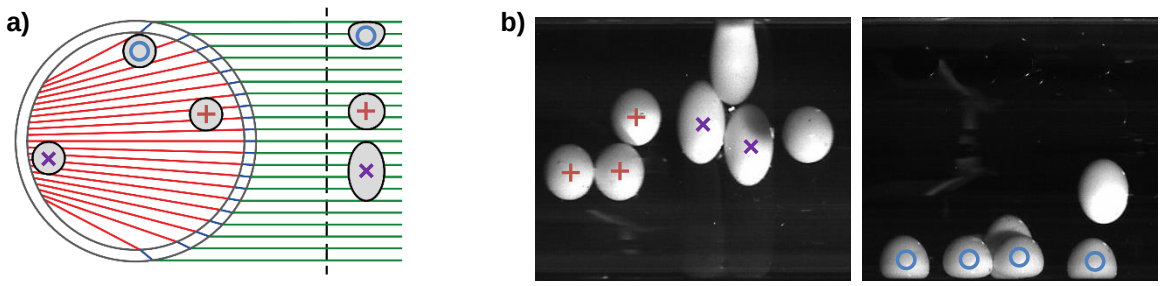

Fig. 4: a) Origin of the non-uniform distortion of the particle images. The lines display the refraction of the camera view in the radial cross-section of the pipe, with the resulting deformation of the particle shape on the right. For comparison, the same deformations can be observed in the snapshots in b).

While the distortion of the particle shapes is easily visible, the challenge for determining the particle locations is the displacement (in Fig. 4a along the vertical direction) of the geometric particle center. Depending on the particle position this displacement can be negligible (e.g. the particle marked with +) or rather large (e.g. the particle marked with o). By combining basic optical laws of refraction with the material properties of the pipe flow experiment, it is possible to calculate how the view gets locally distorted using Snell's law:

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_{glass}}{n_{air}} \quad \text{and} \quad \frac{\sin\theta_3}{\sin\theta_4} = \frac{n_{fluid}}{n_{glass}},$$

In our experiment we use the refractive index of glass $n_{glass} = 1.473$, the surrounding air $n_{air} = 1$ and the fluid in the pipe $n_{flud} = 1.344$ (for the water glycerin mixture, see Meißner et al. 2007) to determine the change of the local incidence angle θ at both interfaces of the pipe wall, as it is illustrated in Fig. 5a. This provides us with a localized optical transfer function from the particle's "pixel position" to its "pipe position". Using a single camera view this allows the determination of the particles' position along a line through the pipe cross-section (in Fig. 4a marked by the red lines inside the pipe). We summarize that the local application of Snell's law allows it to mathematically remove the main optical distortion occurring at the pipe wall. The particle localization along the pipe axis on the other hand is straight-forward, because it does not require a local distortion correction.

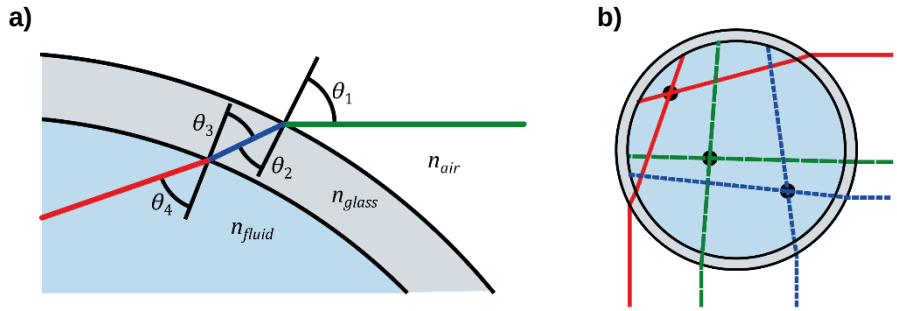

Fig. 5: a) Sketch of the refraction of light at the outer and inner wall of the pipe, leading to the distorted view in the images. b) Sketch of the distortion for different vertical positions in the images. The combination of the two views reveals the true coordinates at the intersection points.

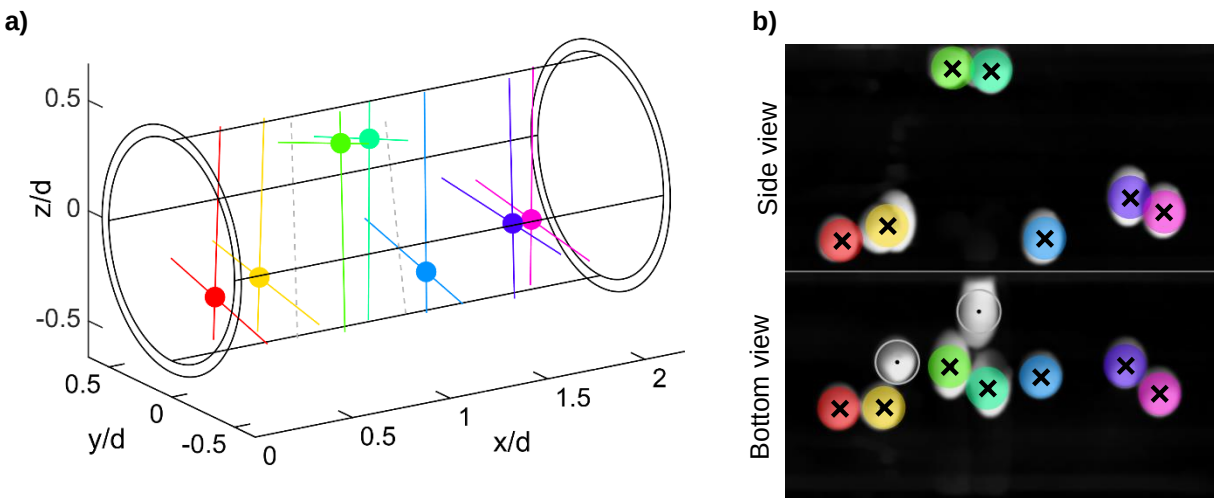

Fig. 6: a) Determined particle coordinates in the recorded pipe section. The solid lines represent the distorted view directions, with the particles positions determined by the intersections. Dashed lines are particles that could not be matched. b) The particle images for the data in a) with the identified particles marked. Note that two particles visible in the bottom view are fully obstructed in the side view (at the top) and could not be paired and located.

Pairing the particles

Based on the information of the geometric particle center gained from a single view, the possible position of a particle can be determined to a line within the observed pipe segment. By combining this information from two orthogonal views the three-dimensional particle position can be detected. The pairing of the particle views is performed within the cross-section (see

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Fig. 5b) and leads ideally to an intersection (the algorithm searches for the minimal distance also in the axial direction). False pairings with intersections outside the boundaries of the pipe are filtered out. If no matching particle in the second view is found, due to overlap or image processing errors, the particles are counted as unpaired. An example of the identified pairs and three-dimensional coordinates from a recorded particle cluster is displayed in Fig. 6.

Assessment

To evaluate the imaging method, we analyzed snapshots of varying particle concentration. As an uncertainty quantification of the particle localization we use the remaining distance when pairing the particles from both view directions. This quantity includes random errors and uncertainties from the image processing and the particle identification as well as misalignments between the two camera views. At a particle concentration up to 1%, the uncertainty of the particle localization is below $0.25d_p$ (for 90% of the paired particles) and on average 91% of the particles are paired. As the particle concentration increases (to 3%, or up to 24 particles in view), the probability of particles overlapping in one of the views and being misidentified as a single particle is higher. In addition, the number of particles that can be paired lowers to 64% and particles with similar axial coordinates are more often mismatched in the pairing process. Overall this leads to a slightly increased uncertainty of the particle localization of up to $0.28d_p$ (for 90% of the particles).
The most common approach to design three-dimensional imaging methods for high particle concentrations is to increase the number of independent views into the experiment. This would allow for a more accurate measurement of the particle positions and would reduce the probability of overlap in multiple views.

Results

We used our method to investigate the migration of particles in a laminar pipe flow, in which the particles enter the pipe with a random spatial distribution. Fig. 7 displays the determined radial particle position $320d$ downstream from the entrance with Reynolds-number $\mathrm{Re} = 1000$. During the experiment the particles exhibited variance in the density, which causes many particles to sink close to the bottom of the pipe at $r = 0.37d$ (due to large particle diameter $d_p \cong 0.2d$ the particles at $r = 0.4d$ are in direct contact with the wall). Despite this shortcoming, the typical effects of inertial focusing can still be observed. More specifically, no particles are located near the centerline most particles are located at $r = 0.24d$, which approximately agrees with the inner annulus measured by Morita et al. 2017.

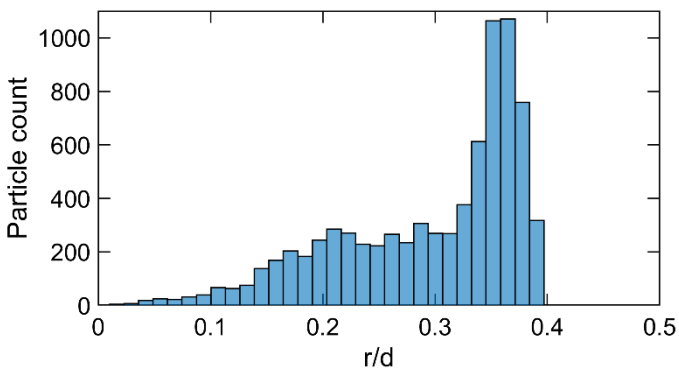

Fig. 7: Statistics of radial particle positions at $320d$ with $\mathrm{Re} = 1000$.

Conclusion

We presented an efficient, image processing method to determine the three-dimensional positions of individual particles and particle clusters in pipe flow with a single camera. By exploiting an analytical reconstruction of the refraction occurring at the curved pipe wall, it was possible to circumvent the implementation of a refractive index matching (e.g. with a box filled with fluid encasing the pipe). As our method does not require costly equipment or other specific modifications to the experiment, it is well-suited for the observation of inertial migration effects, where many statistical measurements at varying axial locations along the pipe are needed.
The main limitation of the method is its decreasing accuracy for increasing particle concentration. This can be improved by increasing the number of independent views, with mirrors or a second camera. When using a high sampling rate recoding, the algorithm can be extended to particle tracking of individual particles, by correlating the three-dimensional positions over time.

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