

# Defocusing Particle Tracking Velocimetry in Thin Annular Rotor-Stator Gaps

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## ABSTRACT

For an in-depth understanding of oil-refrigerant two-phase rotor-stator gap flows, as they occur in rotary positive displacement compressors (RPDCs), rigorous investigations on simplified experimental surrogates of RPDCs are necessary. For the diagnostics of such two-phase gap flows, defocusing particle tracking velocimetry (DPTV) is foreseen to be employed for the liquid phase diagnostics alongside interferometric particle imaging (IPI) and high-speed imaging for the diagnostics of dispersed gas bubbles.

The present work addresses the application of DPTV to a single-liquid-phase flow in a simplified rotor-stator gap-flow setup comprising a rotating cylinder within a stationary glass housing, enclosing a sub-millimeter gap. DPTV was applied successfully to this challenging setup, which is particularly notable by the thin gap height of 0.5 mm, high circumferential rotor velocities of up to  $17.5 \text{ m s}^{-1}$ , and the correspondingly high shear rates, as well as the curved optical access of the setup. Velocity profiles across the gap were derived for Reynolds numbers ranging from 490 to 10 400, and the corresponding transition from a linear profile shape to an increasingly S-shaped profile was observed. Imperfect concentric running of the test-rig rotor is identified as a particularly challenging aspect due to the small gap height and the resulting high sensitivity to even slight concentricity deviations.

The successful application of DPTV for the characterization of velocity profiles in single-phase thin annular gap flow across a wide range of Reynolds numbers is a major step toward comprehensive two-phase diagnostics of oil-refrigerant rotor-stator gap flows. Challenging aspects have been identified, and the route is set for the next steps in developing a measurement framework that can contribute to a better understanding of RPDC rotor-stator gap flow and the associated potential for RPDC optimization.

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## 1. Introduction

In order to increase the efficiency of screw machines such as oil-injected rotary positive displacement compressors (RPDCs), which have important applications in heat pumps and refrigeration cycles, an in-depth knowledge of the oil-refrigerant two-phase surge- and gap-flow scenario between the compressor's rotor and stator is of utmost importance (Nikolov & Brümmer, 2023). The

accordingly required experimental investigations rely on the non-trivial flow measurement of both liquid and gas phases in the annular gap of the RPDCs. To separate the flow topologies and allow rigorous investigations with reduced complexity, one major objective is the investigation of simplified scenarios, where the gap flow between a rotating cylinder and a stationary cylindrical housing is investigated as a surrogate. In such thin annular gap setups, both the flow of a single liquid phase and the more complex disperse gaseous two-phase flow can be accurately studied. Since the corresponding measurement volumes have a large aspect ratio comprised of a sub-millimeter gap height and a large field of view across the lateral surface of the gap, and optical access is limited, defocusing methods are particularly candidating for this application.

Leister et al. (2022) successfully demonstrated the applicability of defocusing particle tracking velocimetry (DPTV) and interferometric particle imaging (IPI) for two-phase flow diagnostics in thin annular gaps in a table-top proof-of-concept study. Furthermore, the influence of curved surfaces, serving as optical access points, on the shape of particle images (PIs) has already been addressed to take additional advantage of the PI-shape for an advanced data-processing approach in the context of the present annular gap-flow application (Lange et al., 2024). Likewise, the applicability of selected fluorescent tracer particles under elevated temperatures and pressures relevant to compressor applications has been shown by Lange et al. (2025), and first DPTV measurements have been performed in a purpose-built gap-flow test rig to ensure the applicability of DPTV to thin annular gaps for realistic gap dimensions (Lange et al., 2025a).

To advance beyond the above-outlined efforts, the objective of the current investigation centers around the characterization of the circumferential velocity profiles across the gap ( $u_\varphi(r)$ ) in single-phase liquid flow for varying angular velocities  $\Omega$  of the rotor up to revolution speeds of  $40 \text{ s}^{-1}$  and corresponding circumferential velocities of  $17.5 \text{ m s}^{-1}$ . The Reynolds number  $\text{Re} = \Omega R_i h / \nu$  accordingly ranges up to 10 400 with inner gap radius  $R_i$ , gap height  $h$  and kinematic viscosity  $\nu$ .

## 2. Experimental Approach

The gap-flow test rig and experimental setup are sketched in Figure 1. The centerpiece of the gap-flow test rig is a rotating inner cylinder of  $R_i = 69.5 \text{ mm}$  radius within a glass housing of  $R_o = 70 \text{ mm}$  radius forming a gap of  $0.5 \text{ mm}$  height. The rotating inner cylinder is driven by a closed-loop synchronous motor, enabling precise adjustment of angular velocity  $\Omega$ . The thin annular rotor-stator gap is filled with purified water seeded with fluorescent polystyrene tracer particles (PS-FluoRot, *microParticles*) of  $10 \mu\text{m}$  diameter. The corresponding particle response time calculates as  $\tau_p = d_p^2 \frac{\rho_p}{18\mu} \approx 5.83 \times 10^{-6} \text{ s}$ , assuming a particle density of  $1.05 \text{ g cm}^{-3}$  and a dynamic viscosity of water at  $20^\circ\text{C}$  of around  $1 \times 10^{-3} \text{ kg m}^{-1} \text{ s}^{-1}$  (Raffel et al., 2018; VDI, 2006). The tracer particles are illuminated with  $532 \text{ nm}$  laser light (DM2-532-100-DH, *Photonics Industries*) by an articulated mirror arm (VZ-Beam steering Arm 266/532 nm, *LaVision*) and a volumetric laser

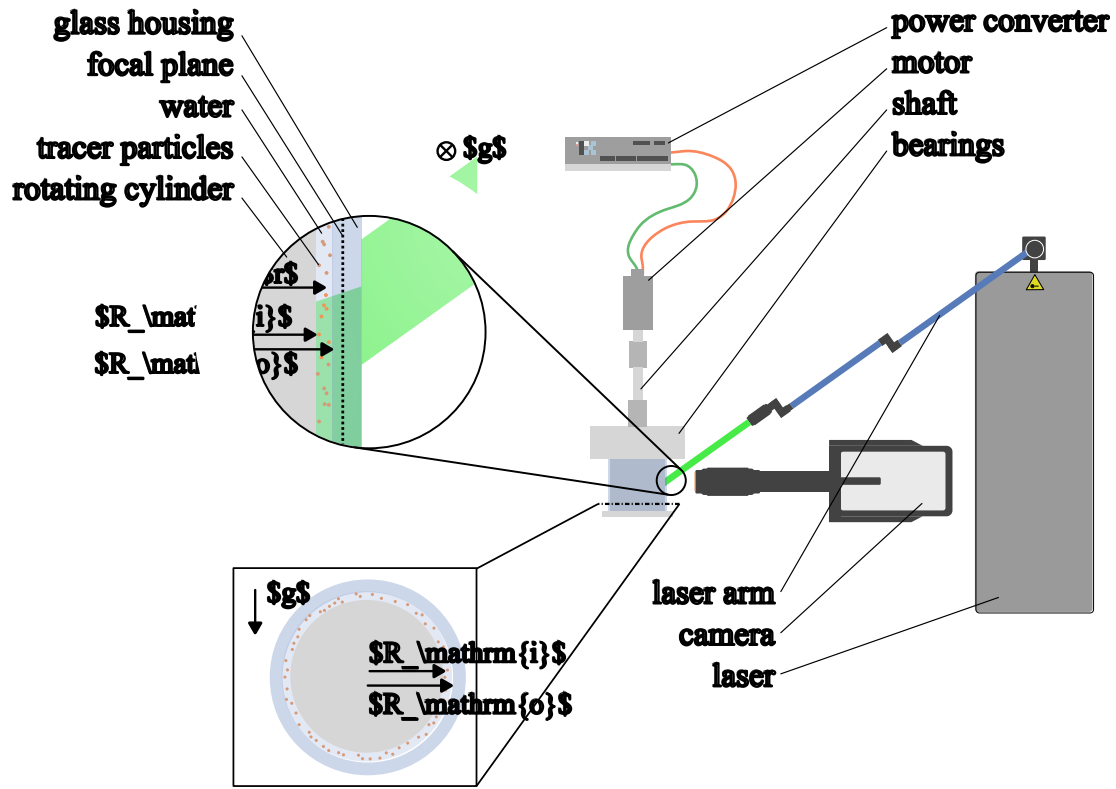


Figure 1. Experimental setup: Gap-flow test rig and laser-optical measurement system.

optics (VZ-Beam steering volume tomo compact, *LaVision*). The tracer particles are imaged by a high-speed camera (Phantom v1840, *Vision Research*, 13.5  $\mu\text{m}$  pixel pitch) and a 100 mm focal length lens at an f-number of 2 (Milvus 2/100M, *ZEISS*). Lens extension tubes were used to decrease the minimum focus distance of the optical setup and thereby increase magnification and optimize defocusing sensitivity (cp. also Leister et al., 2023). A wavelength-dependent cut-off filter in front of the lens was utilized to filter scattered laser light (532 nm wavelength) while transmitting fluorescent light (607 nm). Thereby, visible reflections in the camera images can be avoided while still capturing the tracer PIs. Figure 2 shows a close-up image of the test rig rotor with the incident laser beam to provide a clearer picture on the geometric arrangement of the diagnostics components.

The focal plane of the optical system is positioned within the glass housing, to secure sufficient defocusing for all tracer particles (sufficient distance of all tracer particles to the focal plane, see e.g. Olsen & Adrian, 2000). Thereby, the defocused PI size can be used to derive the particle's position along the optical axis, as the relation between PI size and particle depth position becomes linear in good approximation for sufficient defocusing (Olsen & Adrian, 2000). By that pivotal point of DPTV, it is possible to measure flow velocity in a three-dimensional volume using a single camera, which is particularly useful for the present application with its limited optical access and large aspect-ratio measurement volume (Willert & Gharib, 1992; Fuchs et al., 2016; Barnkob & Rossi, 2020; Leister et al., 2021).

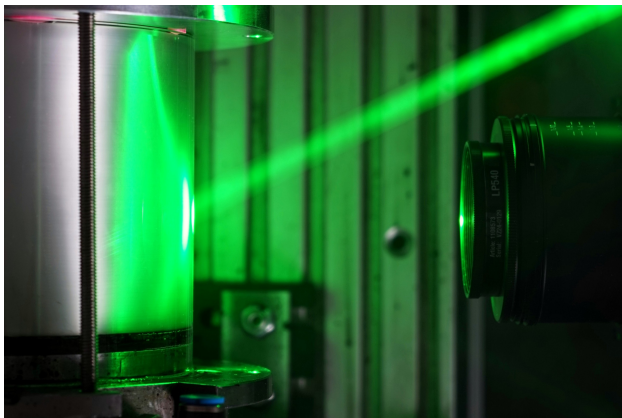


**Figure 2.** Close-up photography of test-rig glass cylinder with rotating inner cylinder and incident laser light.

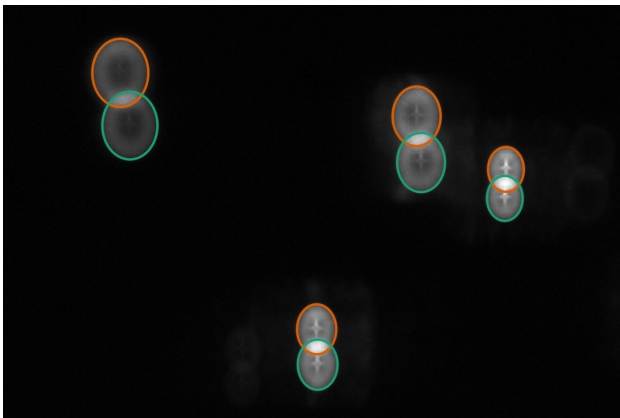


**Figure 3.** Exemplary PIs in two consecutive overlaid frames, with visualization of their detection; astigmatic effect visible by elliptical PI shape.

Due to the astigmatic effect caused by the cylindrical glass housing of the test rig, the optical properties differ between vertical and horizontal image directions. Accordingly, magnification and reproduction scale in the vertical image direction are  $3.25$  and  $4.15\text{ }\mu\text{m px}^{-1}$ , respectively, being affected by astigmatism. In the horizontal image direction, in the absence of the astigmatic effect of the optical access, magnification and reproduction scale are  $2.6$  and  $5.15\text{ }\mu\text{m px}^{-1}$ , respectively. The PI aspect ratio (ellipse major to minor axis ratio) is  $1.24$ . The astigmatic effect on the PI shape is visible in Figure 3. The defocusing sensitivity (relation of particle position shift along the optical axis and PI size change) in the vertical image direction is  $25\text{ }\mu\text{m px}^{-1}$ , and  $28\text{ }\mu\text{m px}^{-1}$  in the horizontal image direction (cp. Leister et al., 2021, 2023). The optical properties as well as the positions of the rotor and the glass housing are estimated in an in-situ manner, as suggested by Fuchs et al. (2016), i.e., from the well-known rotor and stator velocity and the no-slip condition of tracer particles in their direct vicinity. This in-situ calibration approach is highly beneficial for the present application, as target-based calibration would be challenging due to limited space and access to the measurement volume. An overview of the optical parameters is listed in Table 1.

**Table 1.** Optical parameters

|                                                 | Vertical image direction | Horizontal image direction |
|-------------------------------------------------|--------------------------|----------------------------|
| Magnification                                   | 3.25                     | 2.6                        |
| Reproduction scale in $\mu\text{m px}^{-1}$     | 4.15                     | 5.15                       |
| Defocusing sensitivity in $\mu\text{m px}^{-1}$ | 25                       | 28                         |

Measurements were performed at different revolution speed set points ranging from  $2\text{ s}^{-1}$  to  $40\text{ s}^{-1}$ , which corresponds to circumferential velocities from  $0.87\text{ m s}^{-1}$  to  $17.47\text{ m s}^{-1}$  and Reynolds numbers from 490 to 10 400. The investigated revolution speed set points, as well as the corresponding angular velocities, circumferential velocities, and Reynolds numbers, are listed in Table 2.

**Table 2.** Test rig set points and corresponding measurement parameters

|                                                               |                      |                      |                      |                      |
|---------------------------------------------------------------|----------------------|----------------------|----------------------|----------------------|
| Revolution speed in $\text{min}^{-1}$                         | 120                  | 240                  | 720                  | 2400                 |
| Revolution speed in $\text{s}^{-1}$                           | 2                    | 4                    | 12                   | 40                   |
| Angular velocity in $\text{s}^{-1}$                           | 12.6                 | 25.1                 | 75.4                 | 251.3                |
| Circumferential rotor velocity in $\text{m s}^{-1}$           | 0.87                 | 1.75                 | 5.24                 | 17.47                |
| Temperature in $^{\circ}\text{C}$                             | 25                   | 26                   | 26                   | 28                   |
| Kinematic viscosity in $\text{m}^2 \text{s}^{-1}$ (VDI, 2006) | $8.9 \times 10^{-7}$ | $8.7 \times 10^{-7}$ | $8.7 \times 10^{-7}$ | $8.4 \times 10^{-7}$ |
| Reynolds number                                               | 490                  | 1000                 | 3010                 | 10 400               |
| Inter-frame time in $\mu\text{s}$                             | 250                  | 125                  | 41.67                | 12.5                 |
| Recording mode                                                | Continuous           | Continuous           | Continuous           | Double-frame         |

It was observed that the water in the test rig heated up during measurements, presumably due to an increase in ambient temperature, heat input by the laser, as well as due to dissipation in the flow and friction on the bearings. Therefore, the temperature in the test rig was measured and taken into account regarding viscosity and Reynolds number calculation. The temperature-dependent viscosity of water was estimated based on VDI (2006).

Inter-frame time was adapted to the different revolution speed set points to achieve the same inter-frame rotor displacement for all measurements. Images were captured either continuously, i.e., equidistant in time, or in a double frame manner, depending on the revolution speed and with respect to the limitations of the high-speed camera used. Measurement inter-frame time and recording mode are indicated in Table 2. The measurements were performed with an effective sensor size of  $512 \text{ px} \times 384 \text{ px}$  (width  $\times$  height) corresponding to a measurement volume size of  $2.6 \text{ mm} \times 1.6 \text{ mm} \times 0.5 \text{ mm}$  (width  $\times$  height  $\times$  depth).

### 3. Processing and Results

The recorded images were processed in a custom-built Python framework. PI detection is performed by intensity-gradient-based contour detection and a consecutive ellipse fit. The detected PIs and the thereby located particles are tracked with a nearest neighbor-like tracking scheme, which connects particle positions in consecutive time steps to particle tracks by unambiguously matching particles within a defined range of maximum possible displacement. The results are Lagrangian tracks of the tracer particles in the case of continuous recording and PI pairs with the related displacement in the case of double-frame recording. An overlaid image of two consecutive frames and a visualization of the corresponding PI detections is shown in Figure 3.

For the characterization of the radial profiles of the circumferential velocity  $u_\varphi(r)$ , a reduced image section of  $512 \text{ px} \times 192 \text{ px}$  (width  $\times$  height) was evaluated. Figure 4 shows the displacement of particles between consecutive frames for the  $2 \text{ s}^{-1}$  revolution speed set point. Color indicates rotor phase. Based on this scatter plot, the velocity profile in the gap can already be estimated as the PI major axis corresponds to the particle's radial position  $r$  and the particle's displacement corresponds to the circumferential velocity. Basic binning and averaging of this data reveals an approximately linear velocity profile (Figure 5). Nevertheless, a significant scatter margin is visible in both plots. It is assumed that multiple effects add up to the scatter margin, such as measurement uncertainty, fluid mechanical effects, and imperfections in the test rig's mechanical properties. In particular, imperfect concentric running of the test rig rotor contributes significantly to the scatter margin visible in the Figure 4 and Figure 5. The concentricity deviation (difference of the maximum and minimum radius around the rotor circumference during rotation, built-in in the test rig) of the test rig rotor is about  $50 \text{ }\mu\text{m}$ , which is about 10 % of the nominal gap height of  $500 \text{ }\mu\text{m}$ . This clearly indicates the difficulties in manufacturing a test rig for narrow gap flow investigation.

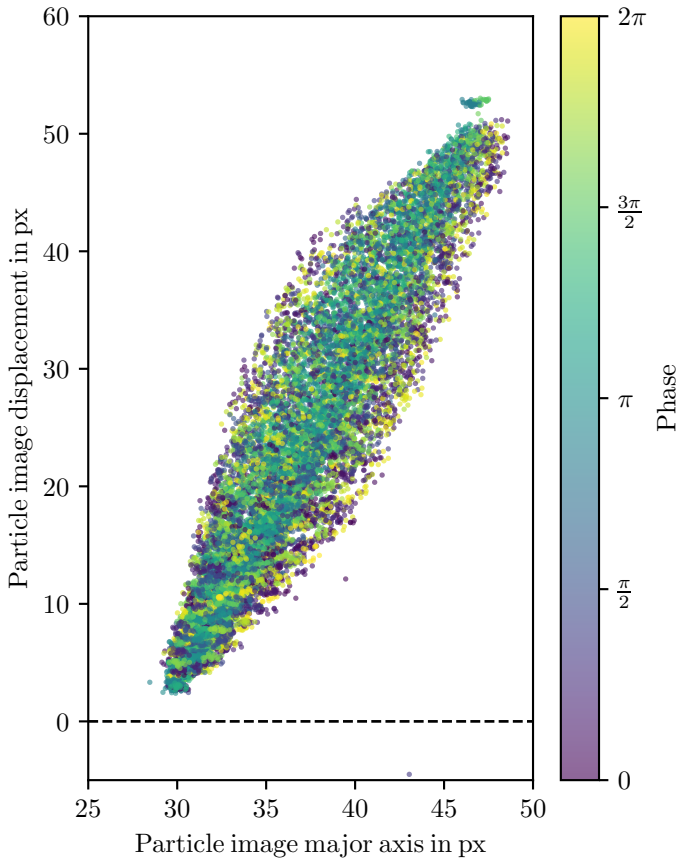


**Figure 4.** Measured PI displacements,  $2 \text{ s}^{-1}$  revolution speed set point.

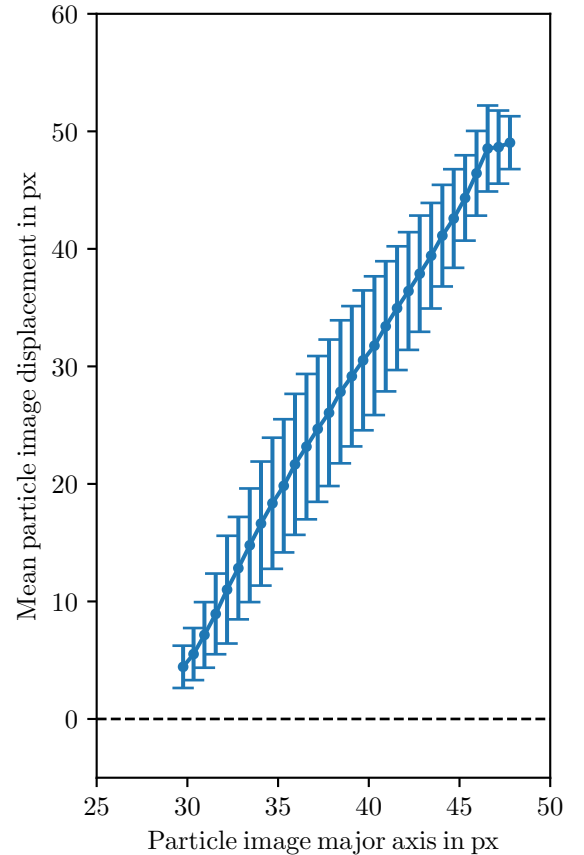


**Figure 5.** Averaged PI displacements, standard deviation error bars.

Data from within a phase window of  $\pi/4$  of the rotor phase is plotted in Figure 6, which demonstrates the significant impact of concentricity deviation on the scatter margin of the measured data. Correspondingly, the binned and averaged data in Figure 7 show a reduced standard deviation in comparison to Figure 5. Also, a strong deviation from the linear profile close to the rotor (i.e., large displacements and large PI major axes) is clearly visible in Figure 5 while being absent in Figure 7. Therefore, it is hypothesized that this might be an artifact caused by concentricity deviation as well.

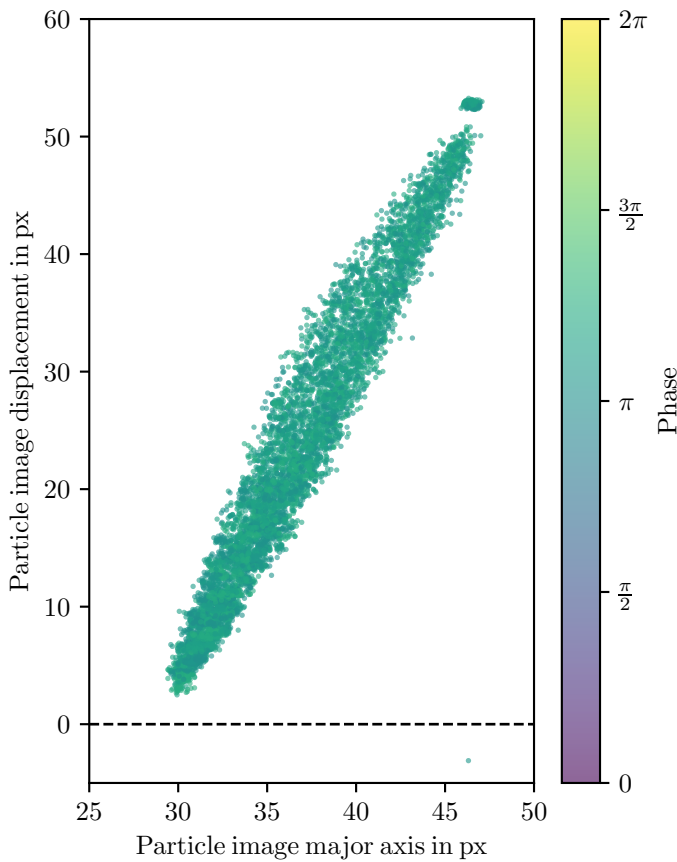


**Figure 6.** Measured PI displacements within  $\pi/4$  phase window,  $2\text{s}^{-1}$  revolution speed set point.

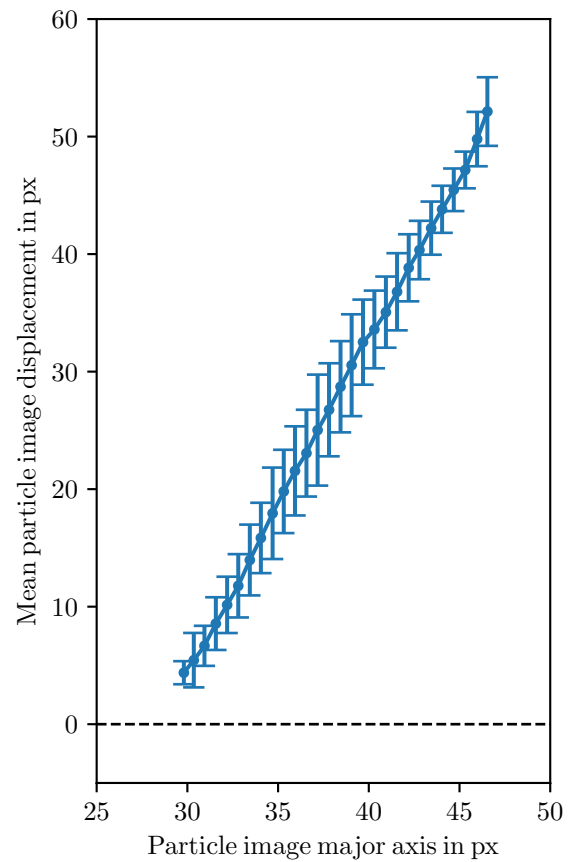


**Figure 7.** Averaged PI displacements within  $\pi/4$  phase window, standard deviation error bars.

Further improvements in the test rig's built quality, as well as approaches like phase averaging, will be employed in future efforts to deal with concentricity deviation and its significant impact on the narrow gap flow. Nevertheless, for the current investigation, which focuses on the measurement-scientific perspective of the problem, the following comparison of velocity profiles at different revolution speed set points is made for the entire data captured, without any phase window applied, despite concentricity deviation and its impact on the mean velocity profiles.

Figure 8 shows the particle displacements after basic binning and averaging for all four revolution-speed set points. The positions of the glass housing and the rotor are estimated based on

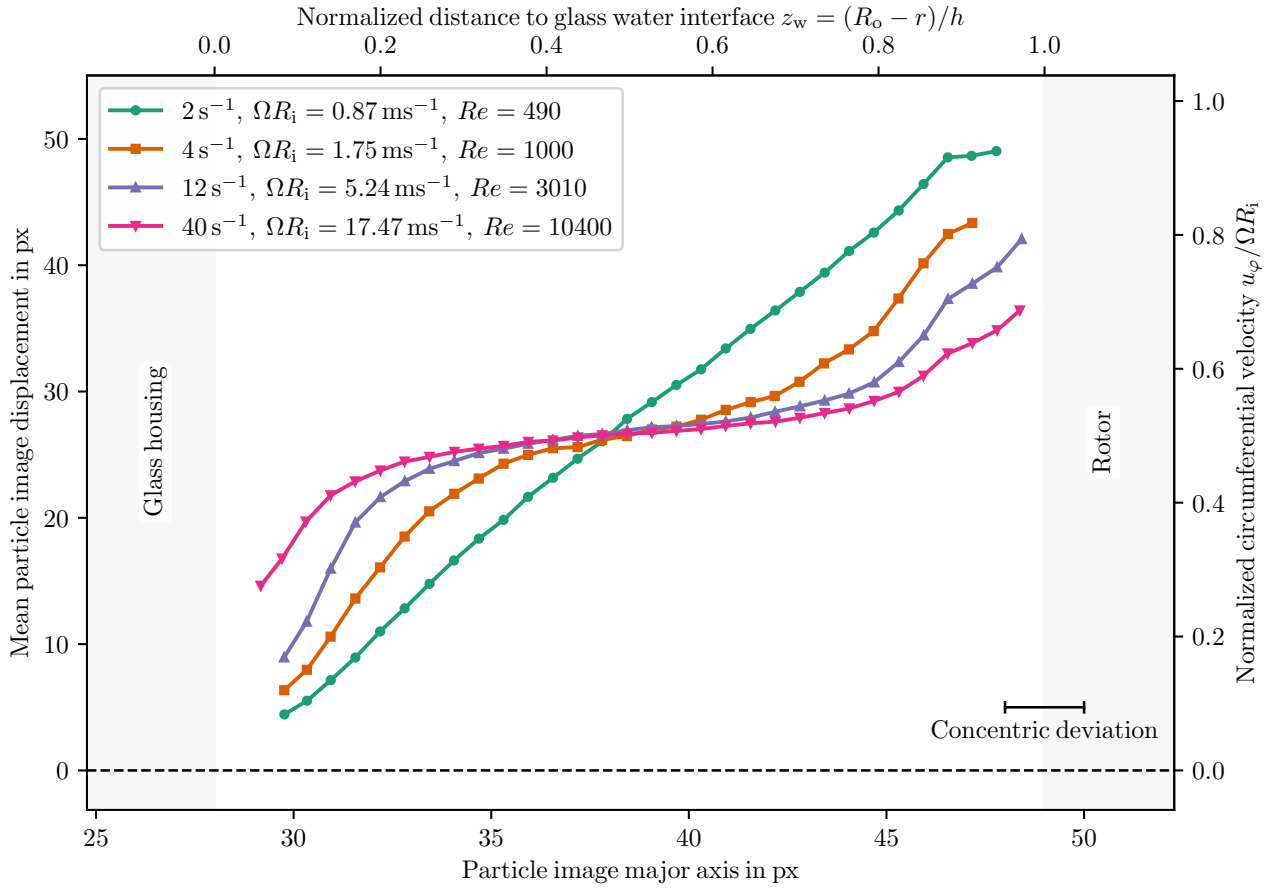


**Figure 8.** Binned and averaged velocity profiles for four revolution speed set points. Estimated glass housing and rotor position are indicated.

the no-slip condition as suggested by Fuchs et al. (2016) in the in-situ calibration approach. Second ordinate and abscissa link the displacement to the corresponding circumferential velocity and the PI major axis size to particle position across the gap, accordingly. As discussed already for the 2 s<sup>-1</sup> revolution speed set point, the velocity profiles show an anomalous course near the rotor, which is assumed to be caused by the imperfect concentric running of the rotor. The concentricity deviation of the rotor is indicated in Figure 8. The measured velocity profiles show a reasonable course. Particularly interesting, the transition from a linear velocity profile to an increasingly S-shaped profile with increasing Reynolds number can be well observed. Being able to resolve velocity profiles across the thin rotor-stator gap for a wide Reynolds number range is seen as a key capability within the foreseen laser-optical measurement framework in the context of RPDCs: The analysis of mean velocity profiles could, e.g., reveal important insights regarding drag torque and possible effects of gas bubbles in rotor-stator gap flows.

#### 4. Conclusions and Outlook

DPTV was successfully applied to a thin annular rotor-stator gap-flow test rig, which serves as a simplified surrogate for RPDCs. Binned, averaged velocity profiles were obtained for a wide range of Reynolds numbers, and the transition from linear to increasingly S-shaped velocity profiles with increasing Reynolds number was observed. This demonstrates the applicability of DPTV for the diagnostics of rotor-stator flows in thin annular gaps, despite being a challenging application with its thin gap height, large shear rates, as well as the astigmatic influence of the curved optical access.

Imperfect concentric running of the rotor was identified as an additional challenge, which was observed to have a significant impact on the flow, as even small concentricity deviations are relatively large in comparison to the small gap height of only 0.5 mm. The obtained velocity profiles show a particularly strong impact of concentricity deviation close to the rotor, as to be expected. Further efforts will therefore focus on improving the concentric running of the test rig's rotor on the one hand, and on phase averaging to tackle the concentricity deviation from both the measurement-scientific and the test-rig accuracy perspective.

DPTV is foreseen to be combined with ongoing IPI efforts (Sax, Dreisbach, & Kriegseis, 2025; Sax, Griesmaier, & Kriegseis, 2025) and high-speed imaging for the diagnostics of dispersed gas bubbles to build a measurement framework for the diagnostics of dispersed two-phase flows in thin annular rotor-stator gaps. This work demonstrates the applicability of DPTV to thin annular rotor-stator gaps and the capability to resolve velocity profiles across the gap. Therefore, it is seen as an important milestone on the way to a better understanding of RPDC rotor-stator leakage flow.

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## Data Availability

A subset of the raw data, as well as processed data, will be made publicly available at <https://doi.org/10.35097/0qhfquswbwpm26b4>. The full raw dataset is available upon request. The Python scripts used for data processing are publicly available at [https://gitlab.kit.edu/heinrich.lange/archimedes\\_a2\\_data\\_processing](https://gitlab.kit.edu/heinrich.lange/archimedes_a2_data_processing). The version used in this work is identified by the tag `lxlaser2026`.

## Nomenclature

|             |                                                        |
|-------------|--------------------------------------------------------|
| $d_p$       | Particle diameter [m]                                  |
| $h$         | Gab height [m]                                         |
| $Re$        | Reynolds number [-]                                    |
| $r$         | Radial coordinate [m]                                  |
| $R_i$       | Inner gap radius (rotor radius) [m]                    |
| $R_o$       | Outer gap radius (inner housing radius) [m]            |
| $u_\varphi$ | Circumferential velocity [ $\text{m s}^{-1}$ ]         |
| $z_w$       | Distance to glass water interface [m]                  |
| $\rho_p$    | Particle density [ $\text{kg m}^{-3}$ ]                |
| $\mu$       | Dynamic viscosity [ $\text{kg m}^{-1} \text{s}^{-1}$ ] |
| $\nu$       | Kinematic viscosity [ $\text{m}^2 \text{s}^{-1}$ ]     |
| $\tau_p$    | Particle response time [s]                             |
| $\Omega$    | Angular rotor velocity [-]                             |

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