

Spectrally separated dual-camera PIV for phase-resolved measurements in oil–water Flows

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ABSTRACT

An experimental approach is proposed for simultaneous, phase-resolved velocity measurements in an oil–water two-phase flow using spectrally separated particle image velocimetry (PIV). The method is developed to evaluate the separation capability of a centrifugal device designed for immiscible fluids with different densities. A dual-camera imaging system is employed, where each camera is equipped with a dedicated optical filter to isolate one phase. The water phase is seeded with rhodamine fluorescent particles. Upon laser excitation, these particles emit fluorescence with a peak wavelength around 585 nm, which is selectively captured using a long-pass filter with a cut-on wavelength of 550 nm. The oil phase consists of a high-density oil-based fluid, seeded with hollow glass microspheres that scatter the incident 532 nm laser light and are recorded by a camera fitted with a narrow-band 532 nm filter. The experiment is conducted in a centrifugal flow configuration, allowing the simultaneous measurement of velocity fields in both phases under identical operating conditions. The spectral separation strategy effectively suppresses optical cross-talk between phases, enabling independent reconstruction of the oil and water velocity fields. The measurements provide quantitative insight into phase distribution, interfacial transport, and flow dynamics relevant to centrifugal separation processes. The present study demonstrates the feasibility and robustness of spectrally resolved dual-camera PIV for complex oil–water flows and highlights its potential as a diagnostic tool for assessing and optimizing centrifugal separation systems.

1. Introduction

Oil–water two-phase flows are encountered extensively in petroleum production, chemical processing, and centrifugal separation systems, where interfacial transport and phase segregation strongly affect process efficiency. The separation efficiency of centrifugal devices critically depends on the velocity fields and phase distribution of the two immiscible liquids. Experimental quantification of these fields, especially with phase-resolution, remains challenging due to optical accessibility and the need to distinguish overlapping signals from each phase.

Conventional particle image velocimetry (PIV) is primarily designed for single-phase flows, requiring tracer particles that follow only one fluid. In liquid–liquid two-phase systems, direct application leads to ambiguous velocity vectors due to optical cross talk from the interface and

particles from the other phase. To overcome this, spectral separation strategies have been developed, where each phase is seeded with different tracers that respond at distinct wavelength bands. Recent applications have demonstrated the feasibility of dual camera, spectrally filtered PIV for bubble liquid flows and for immiscible liquid–liquid systems. (Fan, 2018) developed a novel two-phase PIV technique based on the laser-induced incandescence of tungsten carbide particles, which enables simultaneous velocity measurement of gas and liquid phases in both conventional two-phase flows and flames. Unlike traditional single camera PIV, which is inherently limited to a small field of view, the multi camera reconstruction method proposed by (Liu, 2022) enables more accurate measurements of dispersed phase concentration and velocity in liquid–liquid two phase flows. In this study, we exploit the difference in scattering light wavelengths between different tracer particles to effectively suppress optical cross talk, allowing independent reconstruction of the velocity fields of the oil and water phases.

In liquid–liquid shear flows, the coupling between interfacial dynamics, secondary vortical motion, and centrifugal effects can lead to complex phase migration and slip transport behaviors. Quantitative characterization of the phase-resolved velocity field is therefore essential for understanding the mechanisms governing droplet transport and phase segregation. Among various canonical shear-flow configurations, the Taylor–Couette system provides a well-controlled platform for investigating vortex-driven transport phenomena due to its simple geometry and rich flow instability characteristics. The emergence of Taylor vortices under centrifugal instability introduces strong radial and axial transport, making the TC flow particularly suitable for studying the interaction between coherent vortex structures and oil–water phase distribution.

In this study, we adopt a Taylor–Couette geometry (two coaxial cylinders, inner rotating, outer stationary) as a model flow system. The TC flow exhibits well known transitions from laminar Couette flow to regularly spaced toroidal vortices with increasing inner cylinder Reynolds number. Initially, (Andereck, 1986) systematically revealed the rich flow regimes and their transition characteristics in a concentric cylinder Couette flow with independently rotating cylinders through flow visualization and spectral analysis. They identified several new flow states and clarified the transition boundaries, providing an important basis for subsequent theoretical and numerical studies. While single phase TC flows have been extensively studied for both Newtonian and non Newtonian fluids, investigations of oil–water two phase TC flows are scarce. A few studies have examined drop breakup or phase distribution qualitatively. (Nguyen, 2025) established a unified Taylor analogy model that accurately predicts droplet deformation in low Re shear flows across various viscosity ratios and capillary numbers, capturing the continuous deformation transition with proven experimental reliability. However, due to the lack of suitable

optical measurement techniques, simultaneous phase resolved PIV measurements of velocity fields remain rare.

In oil–water Taylor–Couette flows, the coupling between centrifugal instability, secondary vortical motion, and interfacial dynamics may lead to complex phase segregation and slip transport behaviors. Quantitative characterization of the phase-resolved velocity field is therefore essential for understanding the underlying transport mechanisms and for improving centrifugal separation performance.

This study presents an application of spectrally separated dual camera PIV to an oil–water Taylor–Couette configuration. Simultaneous velocity measurements of the oil and water phases are performed at different inner cylinder rotation speeds under the same operating conditions. The present measurements provide quantitative insight into the coupling between Taylor vortex structures, phase segregation, and interphase slip dynamics in oil–water shear flows.

2. Method

2.1 Taylor–Couette facility

The flow measurements were performed within the annular gap between the two cylinders, corresponding to the annular region commonly encountered in centrifugal separation devices.

Due to the refractive-index mismatch between water and air, light passing through the curved cylindrical wall experienced nonlinear refraction, resulting in significant image compression and distortion near the wall region. To minimize the optical distortion induced by the curved outer cylinder wall, a square acrylic water-filled optical correction box was installed outside the cylindrical test section. Consequently, water existed on both sides of the cylindrical outer wall, significantly reducing the refractive-index transition between media and thereby improving particle imaging quality and velocity reconstruction accuracy near the wall region.

A schematic illustration of the experimental setup is shown in Figure 1.

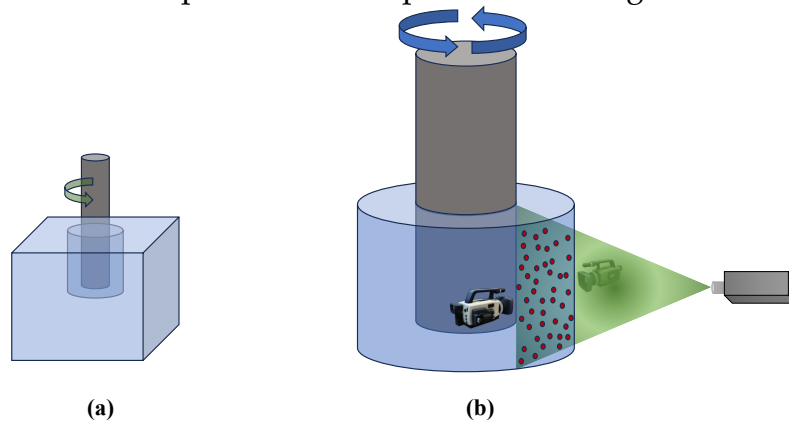


Figure. 1 Schematic diagram of (a) the water-filled optical correction box and (b) the PIV experiment

2.2 Spectrally separated dual-camera PIV system

A spectrally separated (Peterson, 2013) dual-camera particle image velocimetry (PIV) system was developed for phase-resolved measurements in oil–water Taylor–Couette flows. The

measurement principle was based on the wavelength difference between scattering signals and fluorescence emission generated by different tracer particles.

As shown in Figure 2, two synchronized cameras equipped with different spectral filters were used to independently capture the oil-phase and water-phase tracer signals.

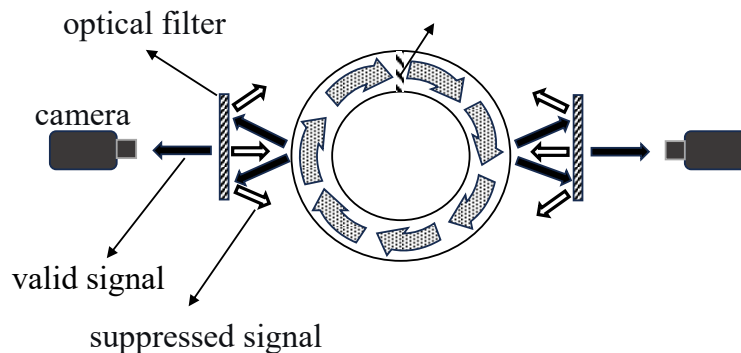


Figure. 2 Top view of the spectral separation configuration

The proposed measurement system provides a reliable technical basis for future simultaneous velocity measurements (Caridad, 2008) of oil–water two-phase flows in centrifugal devices.

2.3 PIV image acquisition and processing

Velocity fields were calculated using the commercial DynamicStudio software based on the cross-correlation PIV algorithm. As illustrated in Figure 3, a small interrogation window was first selected in the first instantaneous particle image at time t_1 . The grayscale intensity matrix within the interrogation window was then cross-correlated with interrogation windows of identical size but different spatial displacements in the subsequent image captured at time $t_1 + \Delta t$. The displacement corresponding to the maximum cross-correlation coefficient was identified as the particle-group displacement ΔX within the interrogation window during the time interval Δt . When Δt was sufficiently small, the local velocity vector could be approximated as $\Delta X / \Delta t$. By repeating this procedure throughout the entire image domain, the instantaneous velocity field was reconstructed.

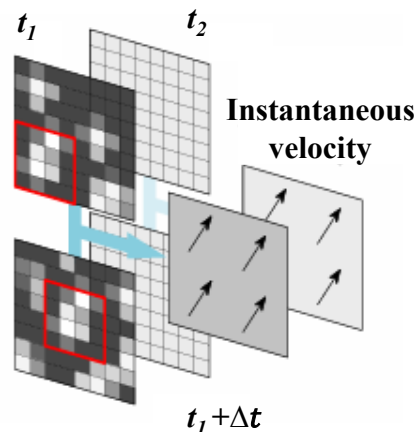


Figure. 3 Interrogation window cross-correlation

The selection of interrogation window size and overlap ratio plays an important role in the accuracy and spatial resolution of PIV measurements. Excessively small interrogation windows may contain insufficient particle images, leading to multiple correlation peaks and increased uncertainty. In contrast, excessively large interrogation windows reduce the spatial resolution of the velocity field and may attenuate local flow fluctuations due to spatial averaging effects. Similarly, insufficient overlap ratios decrease vector density, whereas overly large overlap ratios substantially increase computational cost. In the present study, an interrogation window size of 32×32 pixels with a 50% overlap ratio was adopted for all PIV calculations.

2.4 Vortex identification

This paper employs the λ_{ci} criterion to identify vortex structures in the flow field. The λ_{ci} criterion (Zhou, 1999), also known as the swirling strength criterion, defines the swirling strength via the imaginary part of the eigenvalues of the velocity gradient tensor. This calculation does not retain information about the rotation direction, and it is necessary to combine the local vorticity ($\omega = \nabla \times u$) to determine the rotation direction:

$$\Lambda_{ci}(x, y) = \lambda_{ci}(x, y) \frac{\omega_z(x, y)}{|\omega_z(x, y)|}, \quad (1)$$

Thus, vortices with clockwise rotation ($\Lambda_{ci} < 0$) and counterclockwise rotation ($\Lambda_{ci} > 0$) are distinguished. Wu and Christensen (Wu, 2006) pointed out that adopting a threshold of $|\Lambda_{ci}(x, y)| / \Lambda_{ci}^{rms}(y) > 1.5$ can effectively define the core boundary of vortices and minimize the influence of experimental noise related to the calculation of the velocity gradient. Therefore, for clockwise rotating streamwise vortices in this paper, the definition is given as:

$$\Lambda_{ci}^p(x, y) = \begin{cases} \Lambda_{ci}(x, y) & \text{if } \Lambda_{ci}(x, y) < -1.5\Lambda_{ci}^{rms}(y) \\ 0 & \text{otherwise} \end{cases}. \quad (2)$$

For counterclockwise rotating streamwise vortices, the definition is:

$$\Lambda_{ci}^r(x, y) = \begin{cases} \Lambda_{ci}(x, y) & \text{if } \Lambda_{ci}(x, y) > 1.5\Lambda_{ci}^{rms}(y) \\ 0 & \text{otherwise} \end{cases}. \quad (3)$$

3. Results and discussion

Prior to the phase-resolved oil–water measurements, single-phase water experiments were first conducted to validate the performance of the developed PIV measurement system and to investigate the evolution of Taylor vortex structures under different rotational conditions. The experiments were performed at inner-cylinder rotational speeds of 300, 400, 500, 700, 1000, and 1200 rpm.

3.1 Evolution of Taylor vortex structures

Figure 4 presents the time-averaged axial velocity (V-direction velocity) contours at inner-cylinder rotational speeds of 300, 400, and 500 rpm. The white regions in the contours indicate the masked area corresponding to the rotating cylinder position. Distinct Taylor vortex structures can already be identified within the annular gap at all investigated rotational speeds. As the rotational speed increases, the vortex structures become progressively more pronounced, accompanied by a noticeable increase in the magnitude of the axial velocity.

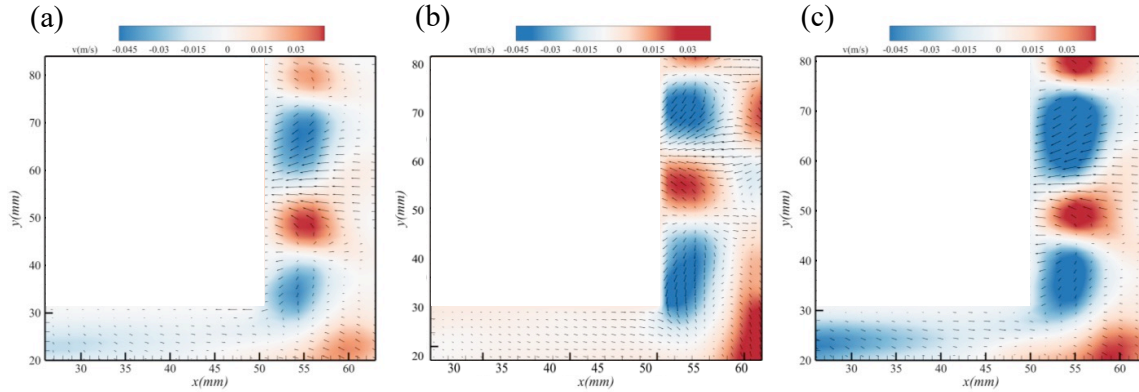


Figure. 4 Axial velocity (V-direction) contours at (a) 300 rpm, (b) 400 rpm, and (c) 500 rpm

At 300 rpm, relatively weak secondary flow motions are observed, and the vortex boundaries remain comparatively diffuse. With increasing rotational speed to 400 rpm, the alternating positive and negative axial velocity regions become clearer, indicating enhanced axial transport induced by the Taylor vortices. When the rotational speed further increases to 500 rpm, the vortex structures exhibit significantly stronger axial velocity intensities and more coherent periodic distributions along the axial direction. The enlarged high-velocity regions demonstrate that the centrifugal instability becomes increasingly dominant with increasing Reynolds number, thereby strengthening the recirculating secondary flow within the annular gap.

These results indicate that the developed PIV measurement system is capable of clearly resolving the evolution of Taylor vortex structures under different operating conditions and provides reliable flow-field measurements for subsequent phase-resolved investigations.

3.2 Comparison of vortex structures between water and oil phases

Meanwhile, 20 μm hollow glass microspheres suspended in glycerol were used to scatter the laser, and the scattered light was captured through a narrowband filter placed in front of a second camera. As shown in Figure 5, the λ_{ci} criterion was also applied to the time-averaged velocity field of the glycerol phase at 500 rpm for vortex identification and vortex strength calculation. Significant differences in vortex structures were observed between the glycerol phase and the water phase.

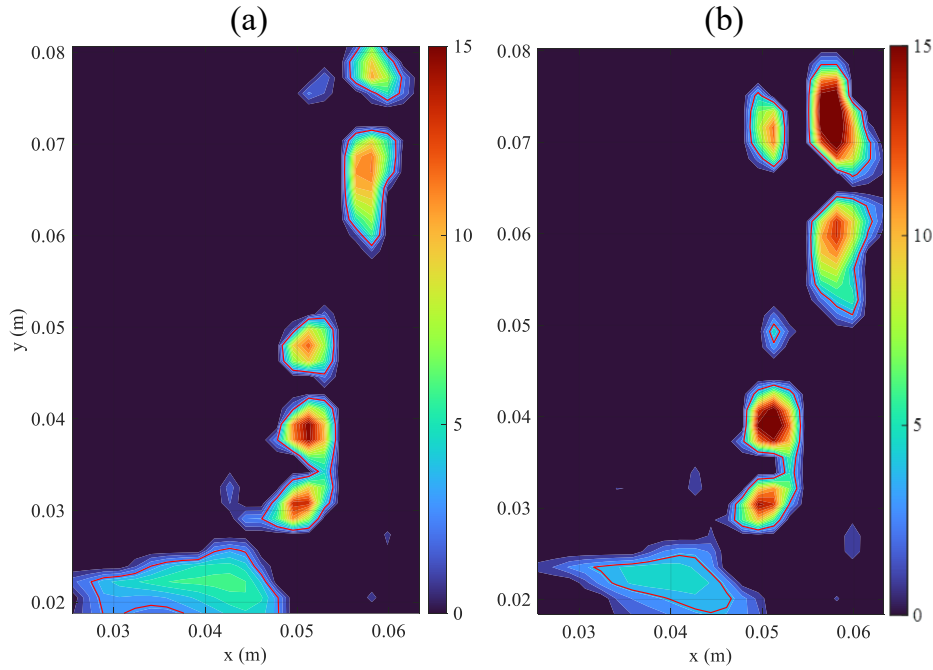


Figure. 5 Vorticity fields of oil phase (a) and water phase (b) at 500 rpm

For the water phase, well-organized Taylor vortex structures are clearly identified within the annular gap. The high- λ_{ci} regions exhibit strong and periodic distributions along the axial direction, indicating pronounced rotational motion and coherent secondary flow structures. In contrast, the glycerol phase exhibits substantially weaker vortex intensity, accompanied by less distinct vortex boundaries and reduced spatial coherence. The regions with elevated λ_{ci} values become noticeably smaller and more diffuse compared with those observed in the water phase.

The suppression of vortex structures in the glycerol phase is mainly attributed to its significantly higher kinematic viscosity. The kinematic viscosity of glycerol is approximately $1.2 \times 10^{-3} \text{ m}^2/\text{s}$ at room temperature, two orders of magnitude higher than that of water. This high viscosity enhances viscous dissipation and weakens the centrifugal instability responsible for Taylor vortex formation. As a result, the secondary flow intensity and vortex-induced momentum transport are considerably reduced under the same rotational condition.

The comparison further demonstrates that the developed spectrally separated PIV system is capable of resolving flow-structure differences between fluids with different physical properties, providing a reliable foundation for future phase-resolved investigations of oil–water Taylor–Couette flows.

4. Conclusions

In the present study, a spectrally separated dual-camera particle image velocimetry (PIV) system was developed and applied to Taylor–Couette flow measurements. By combining fluorescent tracer particles, hollow glass microspheres, optical filters, and synchronized high-speed cameras, independent acquisition of scattering and fluorescence signals was successfully

achieved, providing a technical basis for future phase-resolved measurements in oil–water two-phase flows.

To reduce the optical distortion induced by the curved cylindrical wall, a square water-filled optical correction box was introduced outside the test section. Comparisons of raw particle images before and after correction demonstrated that the proposed optical arrangement significantly improved particle-image clarity and reduced near-wall image distortion, thereby enhancing the reliability of the PIV measurements.

Single-phase water experiments were first conducted at inner-cylinder rotational speeds ranging from 300 to 1200 rpm. The velocity-field results revealed the gradual enhancement of Taylor vortex structures with increasing rotational speed at moderate to relatively high Reynolds numbers. Both the axial velocity contours and the vorticity fields identified using the λ_{ci} criterion showed increasingly coherent vortex structures and intensified secondary flow motions as the Reynolds number increased. At higher rotational speeds, the organized Taylor vortex structures gradually weakened and transitioned toward more complex flow states.

Furthermore, a comparison between water and glycerol flow fields at 500 rpm demonstrated that the vortex intensity in the glycerol phase was significantly weaker than that in the water phase. The higher viscosity of glycerol suppressed centrifugal instability and reduced the strength of coherent vortex structures within the annular gap. These results indicate that the developed PIV system is capable of resolving flow-structure differences between fluids with different physical properties.

Overall, the present work demonstrates the feasibility and effectiveness of the proposed spectrally separated dual-camera PIV system for Taylor–Couette flow measurements. The developed methodology provides a reliable experimental foundation for future investigations of phase distribution, interfacial dynamics, and phase-resolved velocity characteristics in oil–water two-phase Taylor–Couette flows.

Acknowledgments

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