This highlight refers to the PhD Thesis by Willian Hoogendoorn (2021, Cum Laude)

Unveiling laminar-turbulent transition dynamics in particle-laden pipe flows using advanced measurement modalities

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Suspension flows are abundantly present in nature and industry. Typical examples include volcanic ash clouds, sediment transport in rivers, blood flow through human capillaries and the dredging industries. Accurate models of suspension flows are of key importance for prediction, optimization and control of particle-laden flows, especially in industrial applications. However, accurate experimental reference data is hardly available for the development and validation of these models. The opaque nature of suspension flows precludes the acquisition of quantitative flow information by means of established optical measurement techniques. Therefore, we study particle-laden flows using state-of-the-art measurement techniques, including ultrasound, magnetic resonance and optical imaging. In particular, the effect of particles (i.e., size and volume fraction) on laminar-turbulent transition in pipe flow is studied, as suspension flows exhibit a distinctly different transition scenario compared to classical, single-phase transition. The measurement modalities are used to study specific cases in this three-dimensional parameter space (i.e., particle-to-pipe diameter ratio, *d/D*, bulk solid volume fraction, ϕ_b, and suspension viscosity based Reynolds number, Re_s). Each case exhibits characteristic dynamics which underly particle-induced transition (Hogendoorn 2021, Hogendoorn and Poelma 2018, Hogendoorn et al. 2021, 2022). Below, a concise overview is given of the results obtained for various cases.

Velocity statistics in dilute cases using particle image velocimetry

Typical instantaneous flow fields for a particle-induced transition scenario obtained using planar particle image velocimetry (PIV) are shown in Figure 1. Note that u_x' represents the mean-subtracted streamwise velocity component and the mean flow is from left to right. For these experiments a laser light sheet is used in combination with LED back-illumination. In this configuration we are able to simultaneously measure the flow fields at a plane in pipe centre (in the stream-wise direction) and obtain the dispersed phase particles across the complete pipe. From the latter the solid volume fraction is determined. In each image three dispersed phase particles can be observed, where the particles being present in the laser plane show up as bright particles due to overexposure and the particles located outside this laser plane appear as black particles. In particular for the first case, with a suspension Reynolds number, Re_s = 1010, it can be observed that the relatively large particles cause local flow perturbations. The blue-colored vectors show that the particles cause a flow with a locally lower velocity (with respect to the mean flow velocity). This velocity deficit is compensated for at other locations, leading to strong velocity variations in a low Reynolds number pipe flow. In the transition region, Re_s = 2005, elongated flow structures can be observed, which decrease in size when turbulence prevails for higher Reynolds numbers (Hogendoorn et al., 2021).

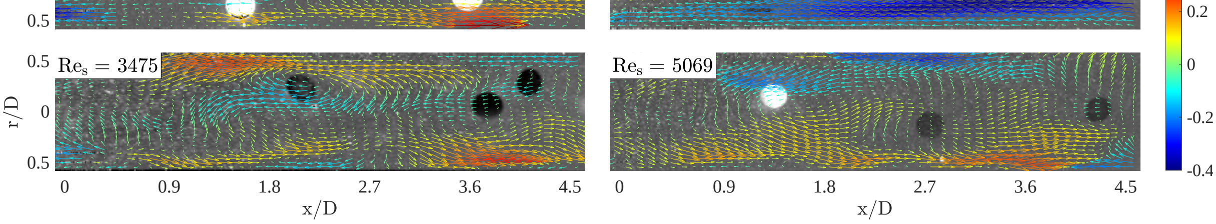

Figure 1: Instantaneous flow fields (obtained using planar particle image velocimetry) are superimposed on the corresponding camera images for a particle-induced transition scenario (d/D = 0.18, ϕ_b = 0.0025). The vector color represents the bulk velocity normalized streamwise velocity fluctuations (u_x'/U_b). For low Reynolds numbers elongated flow structures can be observed, which decrease in size when turbulence prevails for higher Reynolds numbers.

Scan the following QR codes to see movies similar to the vector fields from Figure 1:

S1 - Re = 1010

S2 - Re = 2005

S3 - Re = 4050

Flow visualizations at intermediate volume fractions using ultrasound image velocimetry

Ultrasound image velocimetry (UIV) is used to study the nature of particle-induced transition for higher volume fractions and smaller *d/D*. These results can be seen in Figure 2, where the time traces of the radial velocity component are shown for increasing Reynolds number. From the radial velocity component, the local flow perturbations can be visualized. For this specific case, $\phi_b = 0.14$, it can be seen that the particles introduce flow perturbations, which gradually increase for increasing Reynolds number. Moreover, these perturbations are continuously present along the pipe, even in the transition region. This is in contrast with classical transition, where turbulent patches co-exist with a laminar flow. This UIV result reveals a gradual, particle-induced transition scenario for these conditions (Hogendoorn and Poelma, 2018).

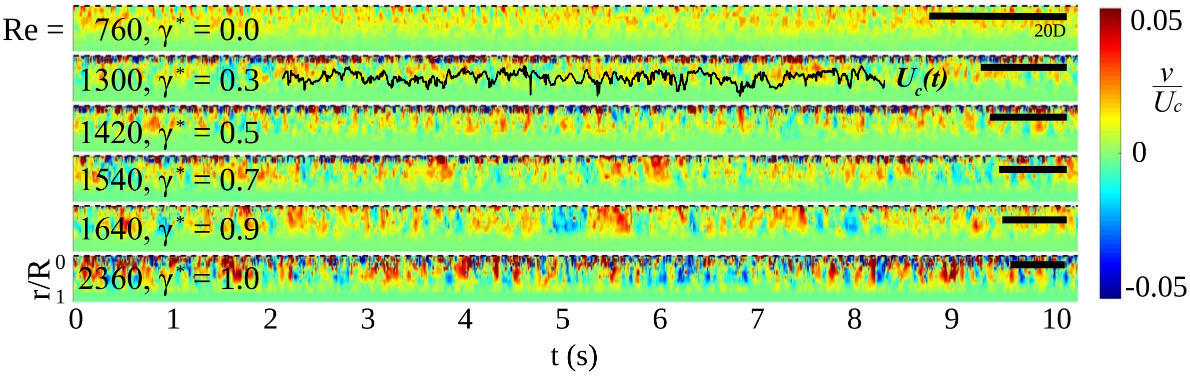

Figure 2: Typical wall-normal velocity time series for different suspension Reynolds numbers for a particle-induced transition case measured with UIV. The (radial) velocity fluctuations gradually increase for increasing Reynolds number and are continuously present along the pipe. For this case the experimental conditions are: ϕ_b = 0.14, and d/D = 0.053.

Unveiling the velocity and volume fraction distributions in dense suspensions using MRI

Magnetic resonance imaging (MRI) is used in order to shed light on the dynamics of dense suspensions. Figure 3 shows the used MRI system with the experimental facility, a typical suspension flow at a bulk solid volume fraction around, $\phi_b \approx 0.5$, captured with optical imaging and typical results in a 'frozen' experiment of particle distributions in a cross-sectional view. Simultaneous measurements of the time-averaged liquid phase velocity and the time-averaged void or solid volume fraction are obtained. Typical results for an approximate constant Reynolds number, $Re_s = 2000$, and increasing bulk solid volume fraction are presented in Figure 4. It can be seen that the velocity profile flattens for increasing solid volume fraction. This is explained by the particle accumulation at the pipe centre (from the bottom panel). This phenomenon is known as shear-induced particle migration. For higher volume fractions, particle rings can be observed in the vicinity of the pipe wall. Here the pipe wall acts as a restriction, which is likely responsible for this ordering. Note that the velocity profile for second case, $\phi_b = 0.08$, deviates from the other cases (ϕ_b= 0, and 0.17). This explained by the corresponding solid volume fraction profile, which shows that the particles are homogeneously distributed across the pipe (not very well visible due to the current color scaling). This is in contrast with the other cases, where shear-induced migration is observed (Hogendoorn, 2021).

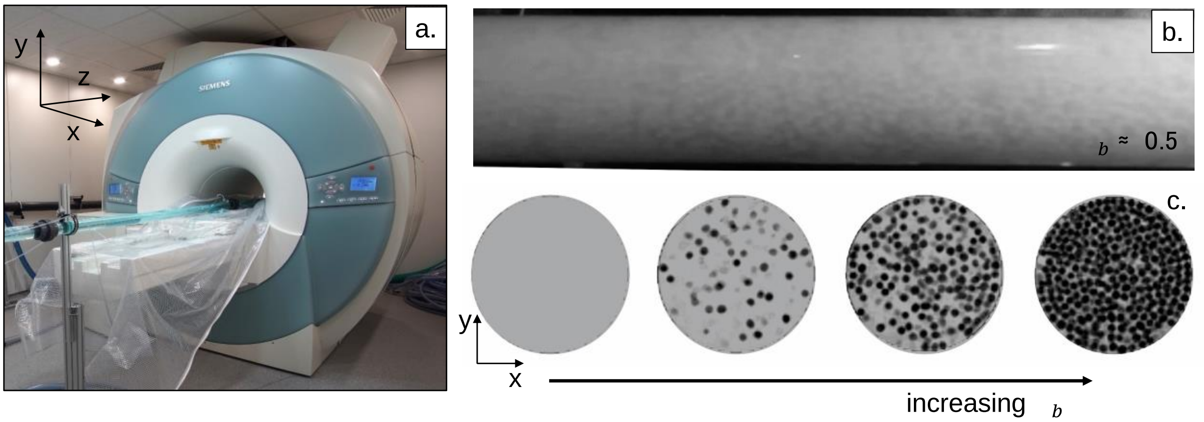

Figure 3: A 3T medical MRI scanner with the experimental facility (a), and an instantaneous camera image from the suspension flow for a dense case with a bulk solid volume fraction, $\phi_b \approx 0.5$ and d/D = 0.058 (b). Particle distributions in the x-y plane obtained using MRI in a 'frozen' experiment for increasing solid volume fraction, up to $\phi_b \approx 0.5$ (c).

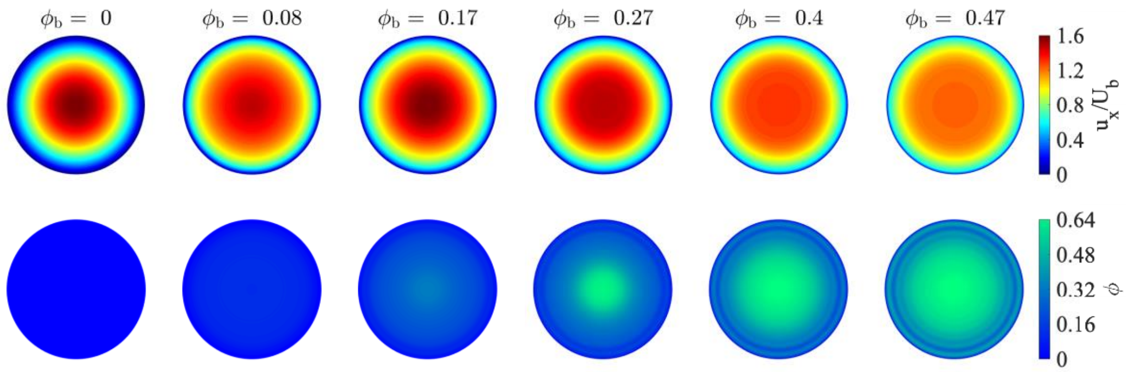

Figure 4: Normalized time-averaged streamwise velocity distributions (top panel) and corresponding time-averaged solid volume fraction distributions (bottom panel) for a constant suspension Reynolds number, $Re_s \approx 2000$, and increasing bulk solid volume fraction obtained using MRI. The velocity profiles are found to flatten for increasing bulk solid volume fraction. For higher volume fractions, particle rings can be observed in the vicinity of the pipe wall.

Conclusion and outlook

Different measurement modalities shed light on different aspects of laminar-turbulent transition in particle-laden pipe flows. For low solid volume fractions and sufficiently large particle-to-pipe diameter ratios velocity statistics are obtained using particle image velocimetry. The particle-induced transition at higher volume fractions and smaller particle-to-pipe diameter ratios is studied using ultrasound image velocimetry. For dense suspensions, MRI measurements were performed in order to obtain average velocity and solid volume fraction profiles. This sheds light on the spatial particle distributions and the corresponding dynamics. For future work advanced MRI sequences will be used to obtain Reynolds stress tensor measurements in suspension flows.

References

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