Unveiling Opaque Flows

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The food processing industry, dredging of rivers, suspension behavior in 3D printer heads and the behavior of blood in our cardiovascular system; they all benefit from a better physical understanding of multiphase flows, as a better understanding will optimize processes and improve predictions.

In our Opaque Flows project, we aim to unveil the physics of particle-laden flows. Next to optical imaging, state-of-the-art techniques such as ultrasound imaging velocimetry (UIV, [1]) and magnetic resonance velocimetry (MRV) are used to study the influence of relatively big, neutrally-buoyant particles in a fluid phase, which is an archetypal suspension. An example of a densely-laden pipe flow, captured with optical imaging can be seen in Figure 1.

Figure 1: Snapshot of a densely laden pipe flow with a particle concentration of 22.5%, captured with optical imaging.

Ultrasound Imaging Velocimetry in Transitional Pipe Flow

UIV has been successfully applied to study laminar-turbulent transition behavior of particle laden flows, with concentrations up to 14% [2]. In this study we show that neutrally buoyant particles completely alter the laminar-turbulent transition behavior.

First, time-averaged pressure drop measurements are performed to characterize the transition behavior (i.e. pressure drop as function of Reynolds number) for increasing particle concentration. For low concentrations, particles cause an earlier onset to transition. Where for a single-phase flow a critical Reynolds number of 2000 is found, this critical Reynolds number is decreasing for increasing particle concentration. Eventually, transition occurs at a critical Reynolds number of around 1350 for a particle concentration of 8%. The decreasing critical Reynolds number can be explained by the perturbations, which are introduced by the relatively big particles (1/19 of the pipe diameter).
In these cases with a moderate concentration, a sharp laminar-turbulent transition is found. However, for higher particle concentrations (i.e. higher than 15%), a smooth laminar-turbulent transition is found, with a monotonically decreasing dimensionless pressure drop (friction factor). This can only be explained by the fact that the transition mechanism changes. To investigate this change, UIV was applied to study two different transition curves more extensively, namely for a particle concentration of 1% and 14%, respectively. For a particle concentration of 1%, turbulent puffs are observed in the velocity fields. These turbulent puffs are characteristic for classic ('single-phase') transition behavior. However, for a particle concentration of 14%, turbulent puffs can no longer be observed in the transition region. Instead, continuous radial velocity fluctuations are observed, which are growing in magnitude with increasing Reynolds number.

**High frame rate ultrasound imaging velocimetry in turbulent pipe flow**

When UIV is operated in plane wave imaging mode, higher imaging rates can be achieved (in the kHz range). This can be leveraged to improve the signal-to-noise ratio, but also to image faster flows (i.e. higher Reynolds numbers). As a proof of principle plane wave imaging UIV is applied to a single phase turbulent flow with a Reynolds number of 44,000 [3].

This high frame rate UIV is applied to turbulent pipe flows. A typical velocity field with a particle concentration of 4%, is shown below. This approach will allow us to continue the investigation of the new particle-induced transition mechanism in a more quantitative way.

![Velocity field with particle concentration of 4%](image)

Figure 2: A snapshot of a turbulent flow with a particle concentration of 4% in a 1-cm diameter pipe, captured with high frame rate UIV. Color represents the radial velocity fluctuations ($v'/U_c$), where the vectors are the absolute velocities.

**References**