PRF # 59468-UNI9: Investigation of velocity fluctuations and correlations during the sedimentation of dense granular dispersions

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Research goals

The project aims to characterize the relative motions of particles within a dense granular dispersion sedimenting under gravity. Using the Péclet number (Pé) as our control parameter, we will assess how the nature and scale of particle motions are correlated with the bulk sedimentation behavior. Specifically, we are interested in understanding a recent discovery that the hindered settling function for systems at low Reynolds numbers exhibits two branches (see Brzinski and Durian, Phys. Rev. Fluids 3, 124303, 2018). Particle motion is characterized using a combination of dynamic light scattering techniques and particle image velocimetry (PIV).

Research Activities

In this first year of the research project, we have focused upon refining and building our experimental capabilities. While expanding our dynamic range beyond that explored in our preliminary data, we encountered technical challenges in generating uniform dispersions for grainsizes spanning several orders of magnitude due to clogging and variable mixing efficiencies. One undergraduate student (Jonam Walter) redesigned our fluidization/sedimentation cell using a custom-built Tesla turbine pump. A Tesla pump is a centrifugal pump which utilizes co-rotating discs in place of a typical impeller so that the flow is laminar. This experimental innovation has enabled our apparatus to recirculate sediment-laden fluid through the sedimentation cell and a new mixing phase without generating fines or damaging the pump, and has reduced the time required to initialize our experiments by an order of magnitude or more. The new recirculation set-up has been tested and proven effective across the range of grainsizes we plan to study, and for dispersions of particle volume fraction up to approximately 0.50. Photographs and schematics of the improved apparatus are provided in Fig. 1.

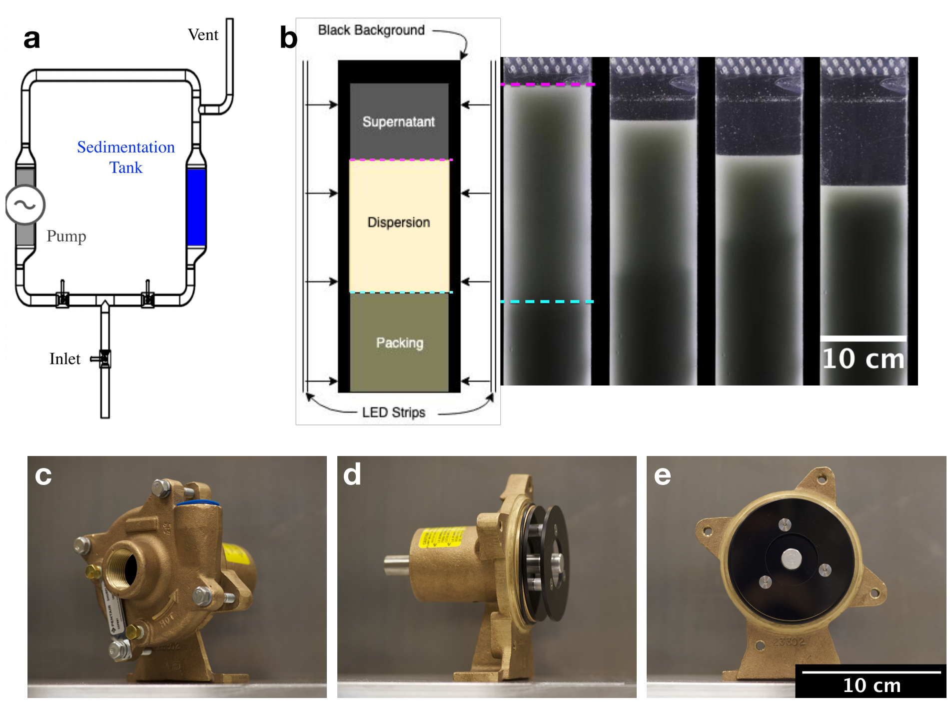

Figure 1: (a) A schematic of the recirculating fluidization/sedimentation system. The sedimentation cell is filled with a uniform dispersion of grains by recirculating the material through the system, including a mixing stage at the top of the sedimentation cell. (b, left) A schematic showing the sedimentation cell, which is side-lit so that the supernatant-dispersion interface can be clearly imaged throughout the sedimentation (right) in order to measure the mean settling speed. (c) A photo of the repurposed, commercial pump housing which houses the new, custom pump rotor. (d-e) Images of the pump with the housing opened to reveal the custom Tesla turbine pump rotor.

Undergraduate student Ryan Tetro built our new dynamic light scattering system. PRF funds facilitated the purchase of the single-frequency laser system necessary for these measurements. Early measurements from the light scattering apparatus are shown in Fig. 2. The fast decay of the variance of the speckle formed by the scattered laser light as a function of the normalized exposure time demonstrates that the nm-scale rearrangements within the dispersion are faster than we expected, thus motivating the use of a faster camera. Undergraduate Ivan Tseytlin began work this summer to integrate a high-speed camera into the light scattering system, as well as to improve our illumination and the contrast of our laser speckle. These improvements are in place and are undergoing final calibration now. Undergraduate Charles Walker also joined the project this summer to build our particle image velocimetry apparatus, though that effort is still in its early stages, with data collection anticipated to begin in Spring of 2020.

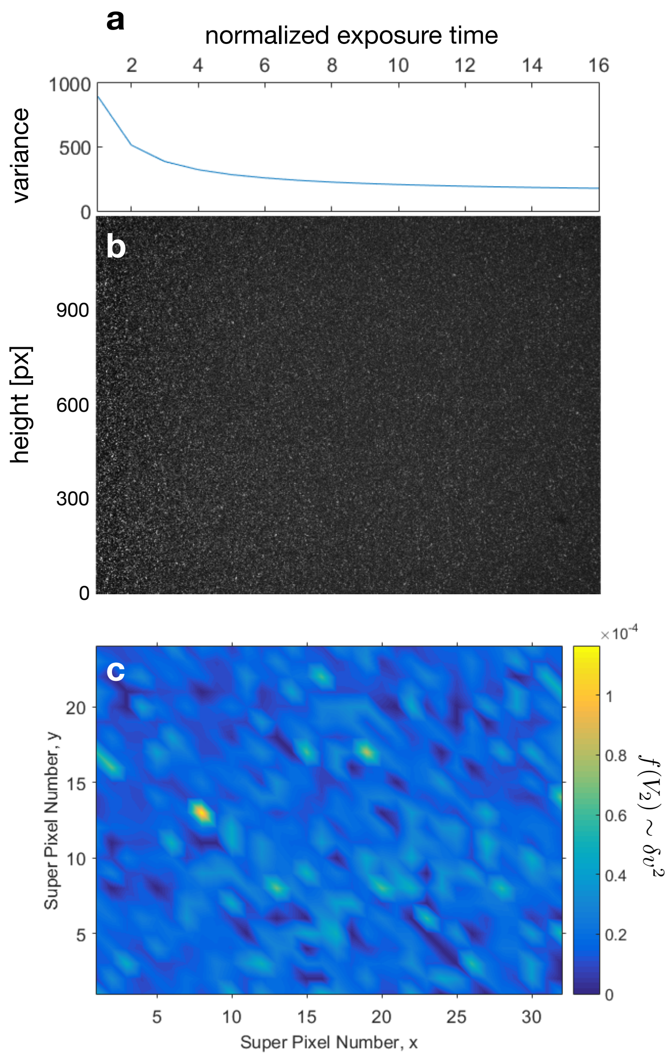

Figure 2: (a) The variance of the speckle pattern from laser light by sedimenting grains plotted vs the normalized exposure time of the speckle image. (b) A space-time plot in which each column of pixels is a line-scan image of the scattered laser speckle, and the x-axis is the normaalized exposure time of the image. (c) A heat-map of the relative velocity fluctuations, as calculated from light scattering data, illustrating the spatially heterogeneous nature of the particle motions.

Our improvements to the sedimentation cell prepared us well to begin systematically exploring the Pè-dependence of the hindered settling function. We will collect and analyze light-scattering data throughout the coming year, and will begin collecting complimentary velocimetry data in the Spring to identify a qualitative change in the particle-scale motion of the dispersed grains that coincides with the transition between branches of the hindered settling function.

We have also expanded the project goals to include an investigation of how the particle motion depends on fluid properties, which may illuminate the particle-scale mechanics that cause hindered settling. In particular, undergraduate student Shaun Fedrick has initiated a new collaboration with Prof. Paulo Arratia (University of Pennsylvania, Mechanical Engineering and Applied Mechanics) to investigate an alternative, perturbative approach to studying the details of hydrodynamic interactions between particles in a dense dispersion. By using non-shear-thinning viscoelastic fluids, we suppress the particle-streaming typically observed in polymeric fluids and increase the effective extensional viscosity, which dominates during lubrication flows, relative to the shear viscosity. Shaun has developed procedures to prepare the fluids, has characterized their rheology, and will start conducting experiments using them this Fall.

Besides student support, fabrication of our new pump, and the purchase of a laser for light-scattering measurements, PRF funds have supported the purchase of new optical components as well as various other supplies to help produce the experiments and maintain and repair the experimental system.

PRF funds have already supported the senior thesis work of two students (Jonam Walter and Ryan Tetro). In the coming year, I anticipate using PRF funds to support the costs of continued experiments, which will contribute to the completion of 2 more senior theses (Shaun Fedrick and Charles Walker). I am planning for PRF funding to support the participation of one student (Shaun Fedrick) in the American Physical Society's (APS) Division of Fluid Dynamics Meeting in November, and two more students (Ivan Tseytlin and Charles Walker) in the APS March Meeting. I hope to extend support for Ivan Tseytlin's participation in the project and to support two or more additional students' participation through Summer 2020.