PRF#: 57751-DNI9
Annual Report
Pore-Scale Visualization of Clogging and Unclogging Dynamics in Saturated Porous Medium

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Summary

The major challenge for the dynamics of two-phase flow in a porous medium is associated with dynamics of both the carrier phase and the dispersed phase, such as solid particles, oil droplets, or gas bubbles in a complex network. The clogging and unclogging dynamics are interconnected with the 3D trajectories of both phases. We have been focused on two different aspects of this particular problem this year. During this year, the PI moved his lab from the former institution, Penn State University, to Johns Hopkins University. During the lab renovation, he devotes most of his efforts in developing techniques that can address these challenges.

The key accomplishments are summarized as follows:

1. In the first year, we focused primarily on the 2D system and the simplified heterogeneous medium to understand the interaction between flow and the permeability distribution. The goal of the second year is to extend this to the 3D flow configuration.
2. For 3D flow, we developed an in-house dense particle tracking capability, which helps to track over 20,000 particles simultaneously. This concentration is two orders of magnitude larger than the previous technique used with the same visualization setup. The work has been presented in the 13th International Symposium on Particle Image Velocimetry in Munich. The paper has been submitted to Experiments in Fluids.
3. Within the 3D flow, the second phase that can block the pores include the nonspherical particles, oil droplets, or gas bubbles. During our effort last year, we realized that the shape of particles will significantly impact the clogging dynamics. In the second year, we spent time on figuring out how to correctly reconstruct the 3D shape.
4. This project helps to attract several undergraduate students to work on this as research assistants and the results helped us to show students the beauty of fluid dynamics in the junior-level class.

Techniques development

– Parallelized in-house dense particle tracking method (3D Shake-the-box)

An open-source STB code, so-called open source Lagrangian Shadow Tracking (OpenLPT), has been developed and used for testing Lagrangian shadow tracking (LST) in our experimental setup. The original STB method made an assumption that particles used in experiments roughly have the same size and occupy an area of about 3 pixels in diameter on images. This assumption should hold in a laser-illuminated case as one can always choose to illuminate only the focused particles in the interrogation volume. For LST, blurring out-of-focus particles appear to be large and dim on images, potentially breaking the assumption made in STB. By leveraging the synthetic datasets, we addressed all concerns and provided a clear guideline for future experimental setups. The PhD student manages to write the entire code in C++, and this can be run on high-performance computing clusters. In this project, we have successfully used the method to identify the 3D particle velocity, acceleration, and local velocity gradient.

– Complex clogging agent shape reconstruction

We found that the clogging dynamics is very sensitive to the shapes of both the pore network and particles. If the clogging agents in the pores are not just solid particles but deformable bubbles or oil droplets, the shape is not constant, but coupled with the surrounding flow conditions. This will pose additional challenges on the problem. Fortunately, multiple cameras used for tracking particle motion can also be leveraged to study the deformation of the oil or gas phase. We proposed a method to use the visual hull reconstruction to find the 3D shape of the second phase. The method has also been improved through an optimization process using the surface tension.

Accomplishments and Impacts

Accomplishments:

1. We found that clogging initiates when the concentration exceeds certain threshold, which becomes too large for most existing tracking algorithms. This limits the possible quantitative understanding in the problem.
2. Tracking a high-concentration of particles in 3D is a fundamental problem that is associated with the overlapping particles and ambiguity of knowing the exact 3D locations of these particles. This problem was solved successfully with the time-coherence-enforced tracking method.
3. The tracking method has been applied to a back-lit LED system. This system has its great advantage of large area, low cost, and uniform lighting. But it projects both focused and out-of-focus particles on the imaging planes, polluting the results. We solved the problem by using a projection function to separate particles from different focus planes.
4. We show that dense particles tracking can really enhance the statistics and accuracy of tracks from particles.
5. In addition, the deformation of the dispersed phase under strong stretching and non-affine deformation was studied. This is very common in porous medium clogging dynamics due to the presence of oil droplets or residual gas phase.
6. We overcome the fundamental challenges of limited-angle reconstruction due to a small number of fast cameras used in experiments by adding the physical constraint of minimal surface curvature. We named it the virtual camera method. By projecting the reconstructed 3D shape to multiple angles where we do not have actual cameras, the refined images on these virtual camera planes effectively improve the reconstruction quality.

Impact:

1. The code has been shared on GitHub with the rest of the community. So far, four groups from Netherland, Korea, San Diego State University, Wesleyan University have tried the code and provided their feedback.
2. The student that was involved in this project is preparing for his thesis.
3. We have been able to involve two undergraduate students in this project, and they have contributed to the project extensively enough that their names are included in the authors' list of the paper that has been submitted. One of them has graduated and landed a successful mechanical engineer job. The other one decided to pursue graduate program.
4. The results have been utilized as a teaching module to help students to understand the beauty of fluid mechanics and petroleum engineering. This part of the course has been rated as the best in the entire undergraduate fluid mechanics class.
5. The reconstruction code finds its way also in the multiphase flow for oil exploration and oil spill ocean pollution problems.
6. The PI was awarded the Department of Energy ORISE professorship because of this support and its relationship with the fossil energy.