PRF#: 57751-DNI9

Annual Report

Pore-Scale Visualization of Clogging and Unclogging Dynamics in Saturated Porous Medium

P.I. Rui Ni, Johns Hopkins University

Summary

In a homogeneous porous medium, clogging and unclogging will affect the permeability distribution, resulting in a heterogeneous environment with a time-varying permeability field. Although it has been proposed that the flow dynamics is sensitive to the permeability distribution. The competition between hydrodynamics scale and flow scale have not been investigated before. To address this, the first year of efforts are summarized as follows:

1. We have spent significant amount of time on dynamical couplings between flow and clogging induced heterogeneous porous medium.
2. To simply the problem, instead of using clogged medium, we manually insert some obstacles in an otherwise homogeneous porous environment and investigate the influence of these obstacles to the flows.
3. In addition to the heterogeneous porous medium, we also manage to control the flow characteristics by switching it from pressure driven to density driven. This allows us to introduce a flow length scale.
4. The shadowgraph imaging method is developed to quantitatively acquire the flow velocity as well as the density difference.
5. Because of the time limit of the startup, the PI decides to leverage some of the startup resources to support students working on this project in the first year. Although we made significant progress and have one paper in review, the funding was only used to support the PI's time. Most resources will be used in the second year to support graduate students.
6. We have leveraged the startup funds to support students and use the ACS fund to support the PI to work on this project together.
7. 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

- Shadowgraph imaging:

One graduate student was trained to design and operate the shadowgraph imaging system. There has been several iterations of the setup in order for the fluids to be contained without leakage. The vacuum grease was applied to ensure that. In addition, the raw data was not very clean and contaminated with some background noise and light intensity gradient. The PhD student manages to learn how to conduct image processing and data analysis. In addition, the PhD student trained several undergraduate students to conduct the experiments. In this project, we have successfully use the method to identify the location of clogged pores, flow structures, flow velocity, and even density gradient. Although there is some limit of using shadowgraph to extract information on density gradient, the qualitative agreement between the calculated density gradient and measured results from shadowgraph supports our models of mixing and transport of fluids in a heterogeneous environment.

- Refractive-index matching:

We have found out that the refractive index matching technique has some issues in the porous medium environment because it is difficult to get materials' refractive indices perfectly matched. This is not a trivial problem, because 3D particle tracking system relies on triangulation among images in different cameras. The large noise, especially in a small system, becomes challenging to deal with. We spent some time to invent a new technique to deal with large image noise based on an assumption that noise in different images is not correlated. The technique seems very promising in some preliminary test cases. We will continue to develop it to apply it to this study.

Accomplishments and Impacts

Accomplishments:

1. We have built a small setup to generate a homogeneous porous medium, and certain regions in the medium are manually clogged to introduce the heterogeneity of permeability distribution. For the first year, the clogged area is not allowed to move over time to simplify the problem.
2. We found that a porous medium with heterogeneous and anisotropic permeability distribution due to clogging and unclogging is more complicated than what most previous studies suggest, because the permeability distribution turns out to be only one effect.
3. The equally important factor is the competition between the length scale of the flow structures and the typical length scale of the permeability distribution, e.g. the high permeability channels between two clogged zones, is an important factor that controls the transport and mixing in a heterogeneous porous medium. This will in turn affect the clogging dynamics.
4. The shadowgraph imaging system is developed and over forty datasets were collected (each dataset will require at least a day and another day for image processing. The flow is in the Darcy's regime and very slow, and we have to use time-lapse imaging, which takes a long time.)
5. The new particle tracking system is developed to handle noise induced by the mismatch in the refractive index matching process.

Impact:

1. The PI has been able to start his research in the porous medium flow and petroleum field thanks to the gracious support provided.
2. The graduate student working on the project is able to participate in the university symposium to present this work. We have also presented the work to the General Electric Oil and Gas. This project has also been nicely integrated to the Penn State university initiative on energy.
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 PI has utilized this opportunity to organize the PetroChallenge event at Penn State. This event is a collaboration with upstream learning simulator, OilSim, to involve undergraduate students in a game that helps them to explore different decision-making processes in the petroleum industry. Students from different disciplines team up and work to generate revenue for a virtual oil company. The winning team gets to participate in the national competition. The team won the first place in the national competition.