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Measuring and modeling the behavior of a nanoparticle-stabilized CO_2-foam in porous media

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Progress of the research

The first year of this grant was dedicated to study: 1) Generation and transport mechanisms of a foam in porous media and 2) Modeling nanoparticle transport in porous media in the presence of a foam. A summary of the two projects is given herein.

Generation and transport mechanisms of a nanoparticle-stabilized foam in porous media

Foam injection into the subsurface is generally performed to improve gas mobility control in enhanced oil recovery (EOR) and contaminated aquifer remediation. Nanoparticles can improve the stability of a foam and help increasing the performance of the operations. Previous studies focused on foam generation and transport in porous media at the continuum scale. The studies helped to formulate empirical constitutive equations used in mathematical models of foam transport in porous media. However, in order to design foam flooding and create regime diagrams mechanistic constitutive equations are necessary. Moreover, constitutive equations for nanoparticle-stabilized foam are still missing.

This first-year grant period was dedicated to study at the pore scale the generation and transport processes of a foam stabilized with either a surfactant (sodium dodecyl sulfate, SDS), nanoparticles (fumed silica particles, Nycol, U.S.A.), or even a combination of them. A microfluidic system (Dolomite, U.K.) was used for the tests. Upon the selection of the optimal conditions of foamability and stability, a porous medium chip was saturated with a solution containing the surface-active materials and then flooded with nitrogen (N_2) gas at constant rate. Pressure measurements and high-resolution images show that the generation rate and total number of bubbles increases with the injection rate, as well as the uniformity of the bubbles size distribution. An increase in pressure gradient (ΔP, psi) through the medium was recorded during foam generation followed by a sudden drop in ΔP which stabilized around a constant value during foam mobilization. Finally, ΔP decreased steadily during foam coalescence. The same pattern of pressure was observed when stabilizing the foam with any of the three types of solution compositions suggesting same mechanisms of generation and displacement. Figure 1 reports an example of measurements compared with the model.

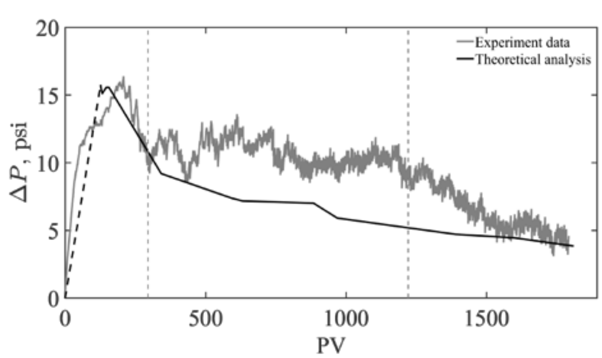

Figure 1. Pressure gradient measured during a test of foam generation and transport through the porous media chip and modeling results.

A mechanistic mathematical model is under development. The model accounts for the generation processes of snap-off, lamella division, and leave-behind. Preliminary results of the calculations are reported in Figure 1. As it is possible to see the model described well the measurements.

The work of this project is in preparation for two publications, namely, 1) Li, Q., Zhang, D., and Prigiobbe, V. (201X). Generation and transport mechanisms of a nanoparticle-stabilized foam in porous media. *In preparation for* Journal of Colloid and Interface Science. 2) Li, Q., Yang, L., and Prigiobbe, V. (201X). Modeling the flow of bubbles in a porous medium. *In preparation for* Journal of Fluid Mechanics.

Modeling nanoparticle transport in porous media in the presence of a foam

Nano-remediation is a promising in situ remediation technology. It consists in injecting reactive nanoparticles (NPs) into the subsurface for the displacement or the degradation of contaminants. However, due to the poor mobility control of the reactive nanoparticle suspension, the application of nano-remediation has some major challenges, such as, high mobility of the particles, which may favor override of the contamination, and particle aggregation, which can lead to a limited distance of influence. Previous experimental studies show the potential of combining nano-remediation with foam flooding to overcome these issues. However, in order to design and optimize the process, a model which couples nanoparticle and foam transport is necessary.

In this project, a mechanistic model at the continuum scale to describe the transport of NPs with and by a foam is presented. The model considers the delivery of nanoscale zero-valent iron (nZVI) and accounts for the processes of aggregation, attachment/detachment, and generation/destruction. Upon validation with literature data, simulations under various conditions of flow, foam quality, and porous medium properties were performed. The calculations show that when NPs are dispersed in the liquid phase, even in the presence of a foam, they may travel much slower than the NPs carried by the foam bubbles (Figure 2). This is because the nanoparticles in suspension are affected by the attachment onto the rock walls and straining at the pore-throats. When the nanoparticle surface is, instead, modified in order to favor their adsorption onto the gas bubbles, NPs are carried by the foam without retardation, except for the small fraction suspended in the liquid phase. Moreover, very stable high quality foam (f_g), i.e., 90-95 vol. % of gas, can be attained using properly surface-modified nZVI (i.e., a nanoparticle-stabilized foam), allowing a significant reduction of water for the operation, while increasing the efficiency of nZVI delivery, even in a low permeability medium within the shallow subsurface. A strong and high quality foam can increase significantly the viscosity of the gas and improve the mobility control of nanoparticles. It is made of 90-95 % of gas and it is therefore an attractive option instead of conventional chemicals used to change the rheological properties of a suspension. In all simulated cases, the pressure within the domain never exceeds values suitable for applications in the shallow subsurface, where foam flooding with NPs is considered to be a promising alternative to the current in situ remediation techniques.

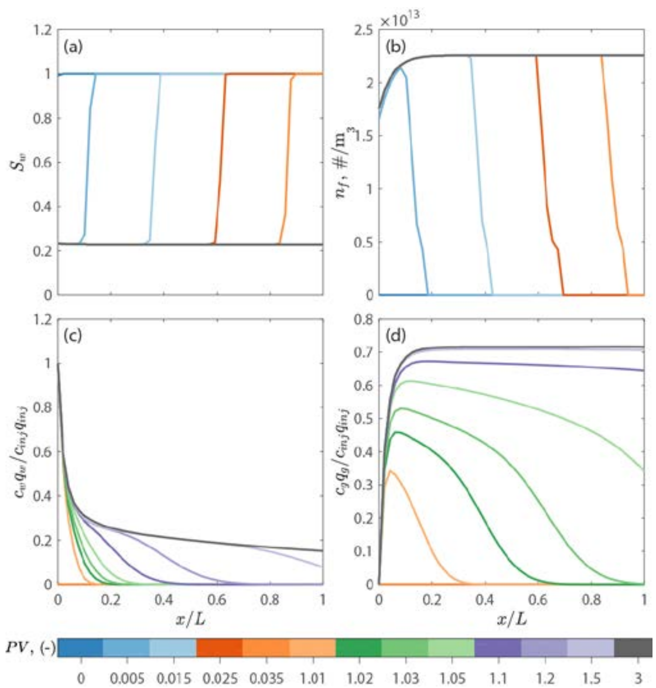

Figure 2. Water saturation (S_w), foam texture (n_f), normalized nanoparticle mass flux in the liquid-phase ($c_w q_w/c_{inj} q_{inj}$) and in the gas-phase ($c_g q_g/c_{inj} q_{inj}$) as a function of normalized distance (x/L).

A manuscript on this project was submitted: Li, Q. and Prigiobbe, V. (201X). Modeling nanoparticle transport in porous media in the presence of a foam. *In review in* Transport in Porous Media

Impact of the research on the career of the PI and student involved

The PI and the students presented at conference and at departmental seminars this projects during the first –year reports, namely:

1. Poster presentation at 8th Northeast Complex Fluids and Soft Matter Workshop: Behavior of nanoparticle-stabilized foam in porous media.
2. Poster presentation at Interpore: Study on the Kinetics of Foam Flow in Porous Media by Microfluidics.
3. Poster presentation at the Gordon conference on Flow and Transport in Permeable Media Across Scales: From Pore-Scale Physics to Geologic-Scale Processes.
4. Invited talk in the Department of Mineral and Energy Engineering at Pennsylvania State University: Nanoparticle-foam transport in porous media.
5. Invited talk in the Department of Civil and Environmental Engineering at Rutgers University: Nanoparticle-foam transport in porous media.
6. Organization of the mini-symposium at Interpore conference: Fundamentals and applications of foam in permeable media