# Editorial to the Special Issue

## Foam in Porous Media for Petroleum and Environmental Engineering—Experience Sharing

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# Editorial to the Special Issue: Foam in Porous Media for Petroleum and Environmental Engineering—Experience Sharing

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The complex behavior of foam in a porous medium has fascinated physicists, engineers, and chemists for decades. Foam is a two-phase dispersion of gas in an aqueous surfactant solution, in this case confined within the complex microscopic porespace of a geological formation. Usually all the gas phase is broken into discrete bubbles separated by thin liquid films called *lamellae*. Usually most of the bubbles are trapped in place by the capillary forces on these lamellae.

Foam has a range of applications when injected into geological formations: enhanced oil or gas recovery (EOR of EGR), aquifer and soil remediation, subsurface sequestration of $CO_2$, and diversion in acid well stimulation. For most applications, the goal is to increase the volume of the reservoir swept by the injected fluids or block one layer in favor of injection into another. Some researchers report that foam also directly displaces trapped oil or waste droplets through the porespace. For the first two applications, the goal is to direct the injected fluids toward regions rich in trapped hydrocarbon or waste. For $CO_2$ sequestration, the goal is to increase the volume of trapped $CO_2$ before vertical migration to the top of the formation can stress and possibly crack the impermeable overburden layer.

Sweep efficiency of the injected gas suffers from three problems: the geological heterogeneity of the formation, the density difference between gas and resident fluids, and the low viscosity of gas relative to resident fluids, which exacerbates the first two problems. Foam directly addresses the viscosity problem by greatly reducing the mobility of gas in the formation. Besides effectively viscosifying the injected fluids, foam also reduces mobility more in high-permeability layers compared to the low-permeability layers, helping to even out flow between them. By increasing the lateral pressure gradient, foam reduces the relative importance of gravity and thus reduces gravity segregation. In addition, in the presence of

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surfactant, foam forms spontaneously as gas migrates upwards across the sharp changes in permeability common in geological formations, further reducing gravity segregation.

This special issue comprises studies directed at all these applications of foam. The papers are grouped here as follows: first, papers on field applications of foam. Papers are then arranged in the order of the process of preparing for a field application: screening surfactants for a particular application; laboratory methods for determining foam properties in more detail; and finally methods for modeling foam behavior, fitting model parameters to data, and understanding, correlating, and predicting foam performance.

"Foam generation, propagation and stability in porous medium," by Skauge et al., briefly reviews recent field applications of foam and highlights crucial aspects of foam behavior for field application in different formations and conditions, to motivate further research. The authors present data for foam inside and outside porous media and discuss mechanisms for foam generation, propagation, mobility, and stability and the effects of surfactant concentration and wettability of the formation.

In "Tracking a foam front in a 3D, heterogeneous porous medium," Boeije et al. present a method for monitoring the effect of foam on sweep efficiency in a formation using measurements of the electrical resistivity in situ. They apply the technique to a $(0.84\ \mathrm{m})^3$ heterogeneous sandpack designed to represent a 5-spot pattern in the field. They then interpret the data using numerical inversion to track the foam front in situ.

Turning to methods to screen surfactant formulations for field application, the next paper is "Correlation between foam flow structure in porous media and surfactant formulation properties" by Chevalier et al. They propose a screening protocol beginning with an examination of foam in bulk (outside porous media), followed by sandpack and then coreflood experiments. They find that the determination of foamability in bulk foam correlates with behavior in porous media. Also, the visualization of local liquid velocity in a sandpack can signal the transition between the two regimes of low-quality (low gas fraction) and high-quality foams.

In "Surfactant foam selection for enhanced light non-aqueous phase liquids (LNAPL) recovery in contaminated aquifers," Longpré-Girard et al. propose a protocol for surfactant selection based first on foamability tests and interfacial tension measurements, followed by sand column tests. They illustrate the protocol with results of a selection process for one application. They find that apparent viscosity in the sandpack in their case correlates with foamability outside the porous medium.

Turning to laboratory studies of foam properties, Gong et al. describe corefloods designed to investigate injectivity in foam SAG processes in "Laboratory investigation of liquid injectivity in surfactant-alternating-gas foam enhanced oil recovery." They find a very slow moving front of foam collapse during gas injection that would greatly affect both gas and subsequent liquid injectivity. During liquid injection, they find that fingering and gas dissolution would affect liquid injectivity.

Janssen et al. compare different immiscible gas injection EOR strategies in "A comparative study of gas flooding and foam-assisted chemical flooding in Bentheimer sandstones" using CT imaging of corefloods. WAG gave better recovery than continuous gas injection. The alkaline surfactant foam process gave the best recovery when near optimal salinity.

Mohanty and Sing examine benefits of silica nanoparticles for foam at high salinity and hardness in "Study of nanoparticle-stabilized foams in harsh reservoir conditions." Tests included bulk foam and emulsion stability tests as well as sandpack tests of oil displacement. The best results were obtained with foam with nanoparticles that selectively plugged the high-permeability sandpack layer.

Brattekås et al. examine foam in fractures in "Foam flow and mobility control in natural fracture networks." Fractured marble was used to minimize matrix flow in the experiments, which also employed positron emission tomography and CT. They observed behavior in the fractures similar to the high- and low-quality regimes seen in porous rock.

Ramadhan and Nguyen employ microfluidic devices to visualize $CO_2$ foam flow in "A pore scale study of non-Newtonian effect on foam propagation in porous media." They find that a surfactant that produces worm-like micelles in the liquid phase offers advantages similar to polymer and is applicable over a wider range of conditions.

Turning to the modeling of foam behavior, Douarche et al. compare modeling approaches in "Calibrating and scaling semi-empirical foam flow models for the assessment of foam-based EOR processes (in heterogeneous reservoirs)." They propose a methodology to fit the parameters of the semi-empirical foam models based on equivalence with the population balance models under steady flow conditions. They propose scaling laws for the effect of permeability on foam properties derived from their data.

Kam and Izadi examine strategies to promote deep foam propagation in a modeling study, "Investigating supercritical $CO_2$ foam propagation distance: conversion from strong foam to weak foam versus gravity segregation." They find that increasing injection pressure and, to a point, reducing foam quality help promote deeper propagation and that the mobilization pressure gradient for foam plays an important part.

Valencia et al. propose a model for a new injection strategy tailored to applications with limited water availability in "Development and validation of a new model for in situ foam generation using foamer droplets injection." The method involves injecting surfactant within tiny droplets dispersed in the gas phase; these find water to create foam in the formation. The model introduces mechanisms for interphase (surfactant) mass transfer into a population balance model for the foam.

The application is remediation for Li and Prigiobbe in "Modeling nanoparticle transport in porous media in the presence of a foam." The nanoparticles react with waste to degrade it as well as aiding in displacement of the waste. The model indicates that nanoparticles attached to bubbles travel faster than particles suspended in the liquid, leading to both nanoparticle and process designs that maximize nanoparticle transport and minimize water requirements.

Almajid and Kovscek compare different mechanisms of foam generation at the leading edge of the gas injection front in a SAG process in "Pore network investigation of trapped gas and foam generation mechanisms." The network-based invasion percolation model includes descriptions of snap-off and lamella division at the front and indicates that lamella division plays a minor role compared to snap-off there.

Simjoo and Zitha employ CT scanning and corefloods in "Modeling and experimental validation of rheological transition during foam flow in porous media." In corefloods with co-injection of surfactant solution and gas, they find a transition from weak foam to strong foam in their experiments at a characteristic gas saturation of $0.75 \pm 0.02$.

Foam application in geological media remains attractive but is not employed on a routine basis as the details of its behavior and the ability to model and predict its performance are improved. The studies presented here advance our understanding toward that goal.