Foam Generation and Propagation in Porous Media

W. R. Rossen¹, G. Yu¹, E. Ashoori¹,³, S. Vincent Bonnieu²,⁴

¹. Delft U. of Technology; 2. Shell Global Solutions International
³. now at Baker Hughes; 4. now at European Space Agency

w.r.rossen@tudelft.nl
What is Foam Inside Porous Media?

- Liquid films separate gas bubbles, reduce gas mobility ("viscosify" the gas)
- Foam is not a new phase, but a two-phase flow phenomenon that drastically reduces gas mobility
- Bubbles are as big as pores
Applications of Foam in Porous Media

- Gas diversion in enhanced/improved oil recovery
- Acid diversion in well stimulation
- CO$_2$ Sequestration
- Liquid or gas diversion in aquifer remediation

In these all cases, foam behavior in pore space is key.

Goal: reduce gas mobility, redirect flow of fluids through geological formations.
Foam Generation in Steady Flow

• Experiments find minimum $\nabla p$ for foam generation in steady gas-liquid flow: \textit{Why?}
• "Lamella division" is crucial step in foam generation
  – requires moving lamellae
  – requires $\Delta p$ across throat $> (2\sigma/R_t)$
• What is minimum $\nabla p$ to mobilize lamellae in pore network?
• Model based on percolation theory predicts a minimum $\nabla p$ for lamella division, foam generation
  Rossen and Gauglitz, \textit{AIChE J.} 36, 1176 (1990)
Results of Percolation Model

- Predicts $\nabla p_{\text{min}} \sim 1/k$, in agreement with $N_2$ data in sandpacks.
- Predicts $\nabla p_{\text{min}}$ lower for hi-$p$ CO$_2$ because of low $\sigma$.
- Model (with adjustable param) fits data for foam generation as function of velocity, liquid volume fraction.

Foam Propagation

• Foam propagation is advance of foam throughout geological formation
• Propagation depends on convection of bubbles, and creation/destruction of bubbles at foam front
• Advance of foam front depends on forward movement of bubbles, plus creation and destruction of bubbles at foam front
• In radial flow from injection well, velocity decreases with distance from well
• Does decreasing velocity hamper ability of foam to advance outward into formation?
Population-Balance Model for Foam Generation as Function of $\nabla p$

- Population-balance foam models represent foam bubble size as explicit variable, resulting from rates of lamella creation, destruction and transport.
- Population-balance model of Kam et al. represents lamella creation as function of $\nabla p$.
- Fits data for foam generation at fixed gas fraction and fixed liquid injection rate.

Kam et al., *SPEJ* 8, 417 (2003); 12, 35 (2007)
Method of Characteristics & Foam

- Consensus: local equilibrium between lamella generation and destruction applies to foam displacements on field scale and even lab scale: exceptions near injection face, at shock fronts
- If local equilibrium applies, and make additional simplifying assumptions, can describe displacement with Method of Characteristics (fractional flow theory, Buckley-Leverett theory)
- Solution depends on behavior at small scale at “traveling wave” at shocks
- Many simplifying assumptions, but useful for insights into complex displacements
Riemann solutions for Shocks

total superficial velocity $u$:
(a) $u=4.5 \times 10^{-5} \text{ m/s}$,
(b) $u=2.798 \times 10^{-5} \text{ m/s}$,
(c) $u=1.5 \times 10^{-5} \text{ m/s}$,
(d) $=1.351 \times 10^{-5} \text{ m/s}$, all with $f_{wj}=0.1$

Foam propagation stops at a velocity (d) at which foam itself is still stable

Ashoori et al., 17, 1231 (2012)
Implications

- There are three separate velocity/$\nabla p$ thresholds: for foam generation, propagation and stability.
- Can foam propagate long distances from an injection well at decreasing velocity, $\nabla p$?
Laboratory Study of Foam Propagation

- Previous experimental studies suggested lower limiting velocity for foam propagation (Friedmann et al., 1986, 1991, 1994)
- Population-balance model suggests lower limiting velocity for stable foam; is this the limit for propagation as well?
- Approach: generate foam at high superficial velocity in-situ, observe foam propagation to sections of larger diameter and smaller $u_t$. Capillary continuity guaranteed.
- Diameter ratio (left to right): 1.0 : 2.7 : 4.0
- Superficial velocity ratio (left to right): 16.0 : 2.2 : 1.0
• Three limiting superficial velocities:
  • $u_t^{\text{gen}}$ – critical velocity for foam generation
  • $u_t^{\text{prop}}$ – critical velocity for foam propagation.
  • $u_t^{\text{col}}$ – critical velocity for foam collapse.

• Find lower limiting velocities for propagation and foam stability; confirms prediction of theory. Foam propagation stops before foam stability limit.
• Study conducted under idealized conditions, w/ stable foam and very high $\nabla p$
• Need to extend and test results at more-realistic field conditions

Yu et al., *SPEJ* (June 2020), 2020; EAGE IOR Symp. 2019
Summary

- Many studies find minimum velocity or pressure gradient for creation of low-mobility foam state in steady two-phase flow
- There are two states at same injection velocity, depending on history: low-mobility foam state and high-mobility coarse or no-foam state
- A population balance model can represent this behavior; suggests also minimum velocity to maintain foam
- Analysis of advancing foam front with this model suggests possible problem with foam propagation far from injection well, based on $\nabla p$ effect on lamella creation; distinct from minimum velocity to maintain foam
  - Need to extend results to more-realistic conditions
  - (There are other ways to place foam far from an injection well besides direct propagation)

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Questions?

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