“CO₂ EOR Projects: Opportunities and Challenges in the Middle East”

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CO₂ FOAM

W.R. Rossen, Delft University of Technology
What is the problem

- \( \text{CO}_2 \) can recover virtually all remaining oil where it sweeps
- Sweep efficiency is often poor because of
  - Reservoir heterogeneity
  - Viscous instability
  - Gravity override
- Foam can help fight all three causes of poor sweep
- Foam improves sweep; \( \text{CO}_2 \) recovers the oil
What is foam?

• 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
What is foam?

- Requires surfactant to stabilize films
- Continuously regenerates in formation; does not have inherent “half life” in formation
- But can segregate and does collapse if it dries out too much
  - critical water saturation for collapse is function of formulation, T, p, formation
- Mechanisms similar for CO$_2$ & other gases
How to inject foam?

- Co-injection of gas and liquid
  - Foam forms in tubing, or else in formation
  - May encounter operational difficulties
- "SAG" (alternating slugs of surfactant and gas)
  - Foam forms in formation
  - Can have excellent injectivity during gas injection; poor injectivity of liquid slugs
- Dissolve surfactant in CO\(_2\); inject no water; foam forms with water in formation
Key foam properties: Two Regimes

- Exists in two distinct regimes depending on "quality" (gas volume fraction)

  - **High-quality regime**: (nearly) Newtonian; diverts flow to lower-permeability layers
  - **Low-quality regime**: shear thinning; does not divert according to perm
Key foam properties: Two Regimes

- Exists in two distinct regimes depending on "quality" (gas volume fraction)

Transition between regimes depends on T, p, salinity, concentration + type of surfactant, formation permeability ...
Key foam properties: SAG process

- SAG is a preferred method of injection
- As gas is injected, get shock front to low water saturation, weaker foam, past range of most lab data
Key foam properties: SAG process

- SAG is a preferred method of injection
- As gas is injected, get shock front to low water saturation, weaker foam, past range of most lab data
- Just behind shock, have relatively low mobility
- Back at well, foam dries out and breaks: high mobility, high injectivity
Foam propagation

• There is no fundamental limit to foam propagation, no “half life” in formation
  • In field, foam observed to propagate 10s m
• Foam requires surfactant, cannot propagate faster than surfactant
  • Simple material balance can give estimate of propagation rate
  • Surfactant stability at high T, salinity?
  • Challenge for surfactant dissolved in CO₂, if surfactant prefers water
• Gravity segregation can limit foam propagation
Foam properties: effect of oil

- Most crude oils destabilize foams made with most surfactants
- Can be considered bad news, or good news
- Heavier oils less a problem than lighter oils
- In lab, with oil in (water-wet) core, sometimes get delay in foam formation
  - Reported as minimum oil saturation for foam; instead probably composition effect
- Fluorocarbon surfactants make stable foams with oil, but are expensive
Foam properties: effect of wettability

- Difficult to make foam in oil-wet formations
- Surfactant can reverse wettability to water-wet, stabilize foam
- If oil is present, it makes this wettability change more difficult
  - Is this just a delay on lab scale?

W. R. Rossen
Key foam properties: Foam in Fractures

- *If* foam is present, it reduces gas channeling in fractures; but would foam form in fractures?
- Foam generation shown in lab in rough fractures 31 and 100 µm wide
- Foam generation less certain if fractures are too wide
- What happens to foam in vugs?
- Alternative: make a foam with cross-linked gel in water
How Does Foam Help?

- Problems: reservoir heterogeneity, viscous instability, gravity override
- Heterogeneous formations: In “high quality regime,” foam reduces mobility more in high-k layers; diverts flow to low-k layers
- Viscous instability: All foams reduce mobility
- Foam increases viscous pressure gradient in competition with gravity; helps fight override
- Foam forms as gas passes sharp permeability boundaries; reduces $k_z$ more than $k_x$
Foam modeling and scale-up

- Current foam simulators can fit the two foam regimes (for co-injection processes)
Foam modeling and scale-up

- Need more data and modeling of behavior important to SAG processes
- Example study w/ N\textsubscript{2} gas, no oil:
Foam modeling and scale-up

• Many effects modeled only empirically:
  • Effect of oil
  • Surfactant concentration
  • Etc. …
• Arbitrary functions represent these factors; effect on results uncertain, especially when extrapolated
• Need more knowledge, *then* better simulators
Foam Field Trials

• Not as many as one would like!
• Steam foam, CA, 1980s (sandstones):
  • Demonstrate propagation to $\geq 90$ ft
  • Surfactant adsorption key to economics
• CO$_2$, USA, 1990s (carbonates):
  • Challenge of foaming in oil-wet formations
  • Foam reduced CO$_2$ injectivity; in some cases CO$_2$ production↓, oil production↑
• HC gas, Snorre field (sandstone), North Sea [1990s-2000s]: delayed gas breakthrough
• HC gas/chemical flood, Daqing, China [1990s]
• Several field trials in planning + execution now
Back-of-envelope checks

• Material balance on gas: If successful, foam leaves large gas saturation in place. Do you have enough gas to sweep region of interest?
• Quick simulation with injection of viscosified gas: needs no special simulator; you can get idea of it helps (neither upper or lower bound)
• Economics: must satisfy adsorption over region swept: cost of surfactant?
• Simple material balances for propagation rate
Knowledge gaps

- Data in range of conditions relevant to SAG
- Foam behavior over wider range of formation types and permeabilities
- Effect of oil and adverse wettability on foam
- Foam behavior in fractures and vugs
- Better surfactants:
  - greater range in T, salinity
  - less adsorption
  - insensitive to oil
Final thoughts

• Foam can address all three causes of poor reservoir sweep: heterogeneity, viscous instability, gravity override
• *Only* foam directly addresses heterogeneity; also special advantages fighting gravity override
• Foam can propagate only as fast as surfactant
• Challenges and knowledge gaps remain
• SAG foam process ideally suited to overcome gravity override in homogeneous formations