GRAVITY OVERRIDE IN CO₂ EOR, AND FOAM

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“All models are false, but some models are useful.”

- George E P Box
Model for Gravity Segregation in Homogeneous Reservoir

At fixed injection rate

At fixed injection pressure

$$p(R_w) - p(R_g) = \frac{k_z \left( \rho_w - \rho_g \right) g}{2 H k_h} R_g^2 \left[ \ln \left( \frac{R_g}{R_w} \right) - \frac{1}{2} \left( 1 - \left( \frac{R_w}{R_g} \right)^2 \right) \right]$$

$$r_g = \sqrt{\frac{Q_t}{k_z \Delta \rho g \pi \lambda_{rt}}}$$

At fixed injection rate, reducing mobility helps; at fixed injection pressure, not

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Gravity Segregation in Homogeneous Reservoir, Radial Flow

- Example: $k_x = 100$ md; $k_z = 10$ md; $r_w = 4$ in; $h = 20$ ft; $\Delta \rho = 963$ kg/m$^3$
- $R_g$ (distance to point of segregation) = 1024 ft; 2048 ft
- $p(R_w) - p(R_g) = 765$ psi; 3310 psi

\[
p(R_w) - p(R_g) = \frac{k_z(\rho_w - \rho_g)g}{2Hk_h} R_g^2 \left[ \ln \left( \frac{R_g}{R_w} \right) - \frac{1}{2} \left( 1 - \left( \frac{R_w}{R_g} \right)^2 \right) \right]
\]
Gravity Segregation in Heterogeneous Reservoirs

- For mild heterogeneity (< ~ 8:1), adjust $k_z$
- With severe heterogeneity, gas bypasses unswept regions within “mixed zone”
- Gas leaks upwards through perm barriers
- Conditions for MC Miscibility may be lost

Stolwijk + Rossen, EAGE IOR Symp., 2009
Model for Gravity Segregation in Homogeneous Reservoir

At fixed injection rate:

\[ r_g = \sqrt{\frac{Q_t}{k_z \Delta \rho g \pi \lambda_{rt}}} \]

\[ p(R_w) - p(R_g) = \frac{k_z (\rho_w - \rho_g) g}{2 H \kappa_h} R_g^{-2} \left[ \ln \left( \frac{R_g}{R_w} \right) - \frac{1}{2} \left( 1 - \left( \frac{R_w}{R_g} \right)^2 \right) \right] \]

At fixed injection rate, reducing mobility helps; at fixed injection pressure, not.

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Gravity Segregation with Limited Injection Pressure: Possible Solution

- Most pressure dissipated near well
- Most segregation occurs far from well
- Increase mobility only near well

\[ r_g = \sqrt{\frac{Q_t}{k_z \Delta \rho g \pi \lambda_{rt}}} \]
• Stimulate the region near injection well
• WAG, especially with large slugs
• Inject water and gas separately, with water above gas
• Inject shear-thinning fluid (foam)
• Inject foam as separate slugs of gas and liquid (SAG)
• Inject foaming surfactant dissolved in the supercritical CO₂; foam forms away from well

SPE 75180, 99794, 112375, 121579, 124197

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How Can Foam Help?

- Reduces mobility
- Heterogeneous formations: Can reduce mobility more in high-k layers; diverts flow to low-k layers
- Spontaneously forms at sharp permeability boundaries; reduces $k_z$ more than $k_x$
- In SAG, can do all this with good injectivity

\[
r_g = \sqrt{\frac{Q_t}{k_z \Delta \rho g \pi \lambda_{rt}}}
\]

\[
p(R_w) - p(R_g) = \frac{k_z (\rho_w - \rho_g) g}{2 H k_h} R_g^2 \left[ \ln \left( \frac{R_g}{R_w} \right) - \frac{1}{2} \left( 1 - \left( \frac{R_w}{R_g} \right)^2 \right) \right]
\]
SAG - Principle

- At injection well, during injection of gas, foam dries out and collapses; injectivity rises
- Away from well, where slugs mix, mobility is *much* lower
- Gravity segregation determined by injection rate, mobility away from well
- Injectivity plunges during liquid injection
  - best to use only one slug of liquid, then gas
  - placement of surfactant tricky
- Also assumes unlimited CO$_2$ deliverability

\[ r_g = \sqrt{\frac{Q}{k_z \Delta \rho g \pi \lambda_p}} \]
Simple model gives quick estimate of distance foam can travel in best case (SPE 75180)

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SAG in Simulations: Layered Formation

Gas saturation at gas breakthrough

Surfactant concentration at gas breakthrough

SPE 1215817

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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
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?
• Do quick simulation with injection of viscosified gas: needs no special simulator; see if 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
Summary

• Gravity segregation is competition between horizontal viscous $\nabla p$ and $\Delta \rho g$
• Simple formula describes segregation in relatively homogeneous formations
• If injection pressure is limited, need to increase injectivity while maintaining low mobility away from well
• In principle, foam can reduce segregation
• Data on foam is limited, as are $\text{CO}_2$ foam field trials. Some trials are in planning or underway
Questions?