"CO_2 EOR Projects: Opportunities and Challenges in the Middle East "

SPE Applied Technology Workshop

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CO_2 FOAM

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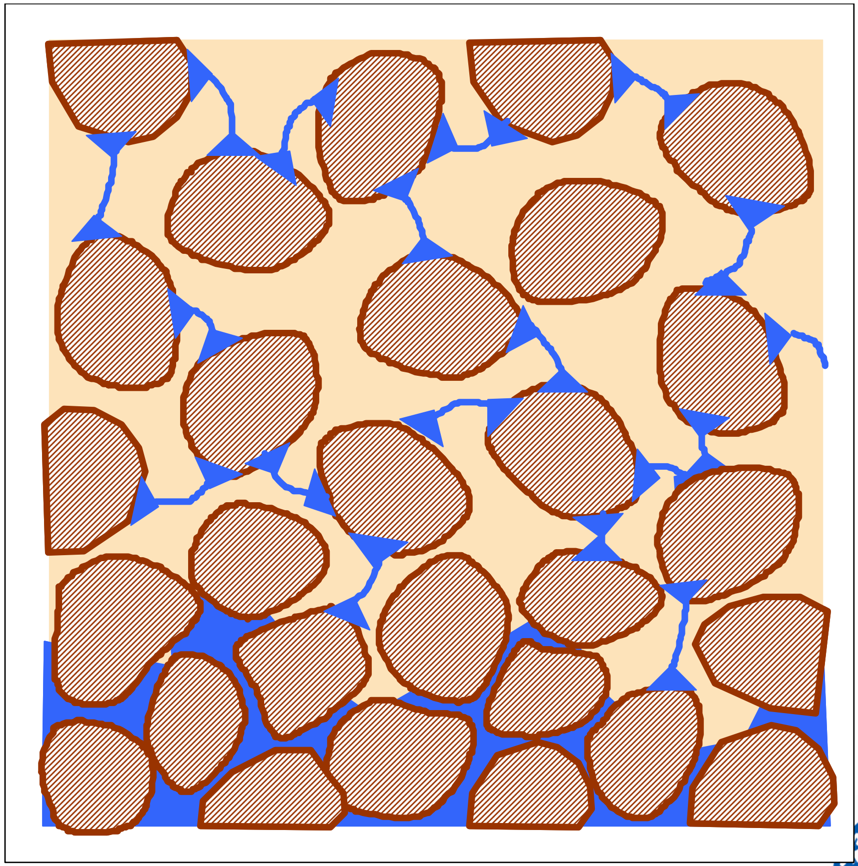
What is the problem

- 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; *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



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What is foam?

- Requires surfactant to stabilize films
- Continually 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 perational 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

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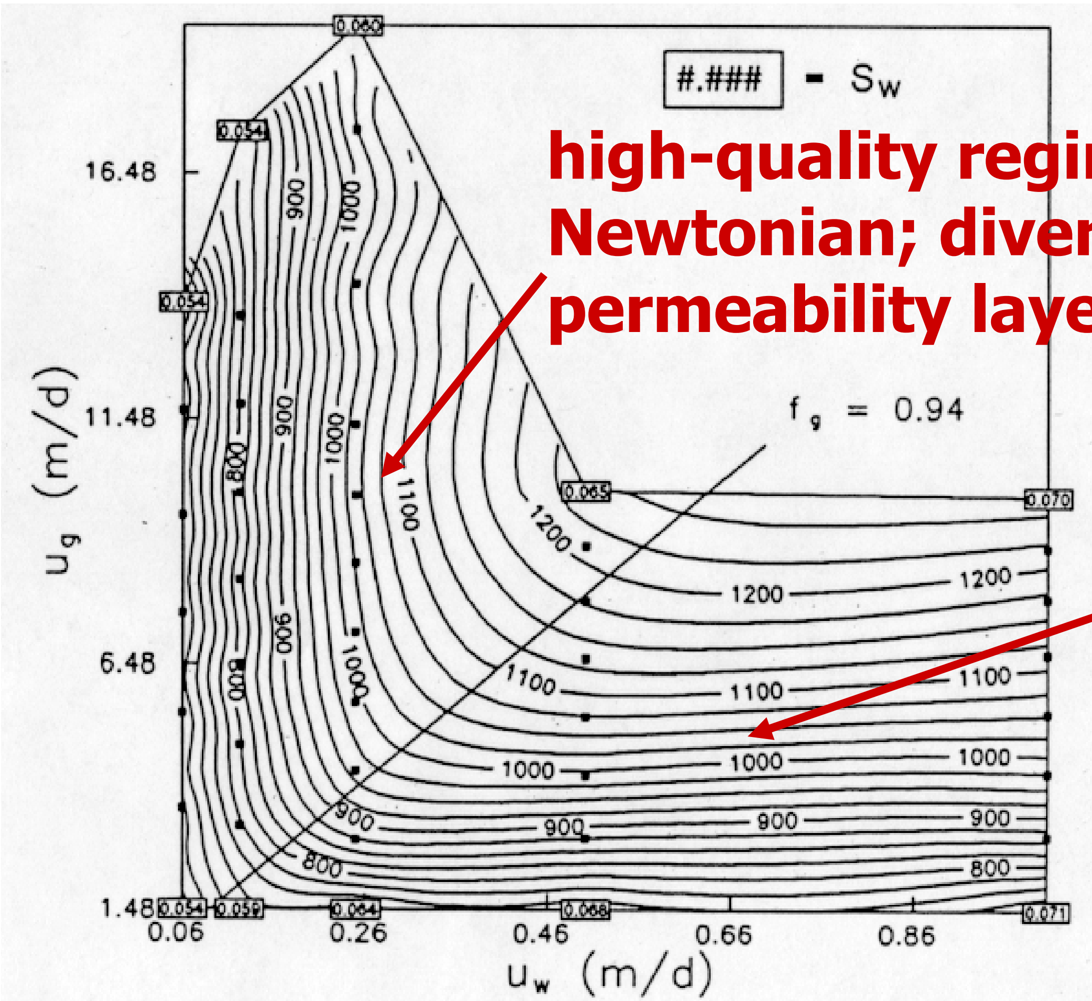
Key foam properties: Two Regimes

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

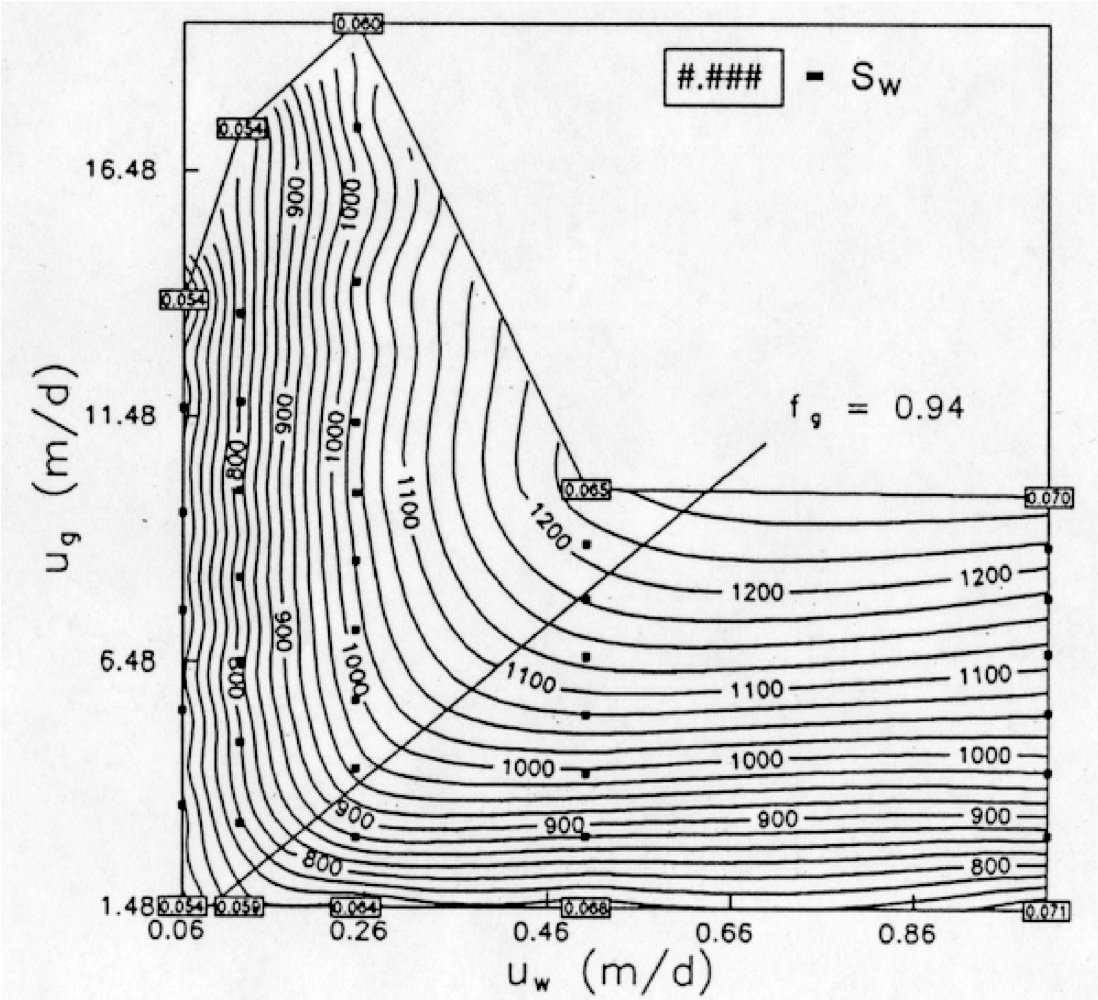


high-quality regime: (nearly) Newtonian; diverts flow to lower-permeability layers

low-quality regime: shear thinning; does not divert according to perm

Key foam properties: Two Regimes

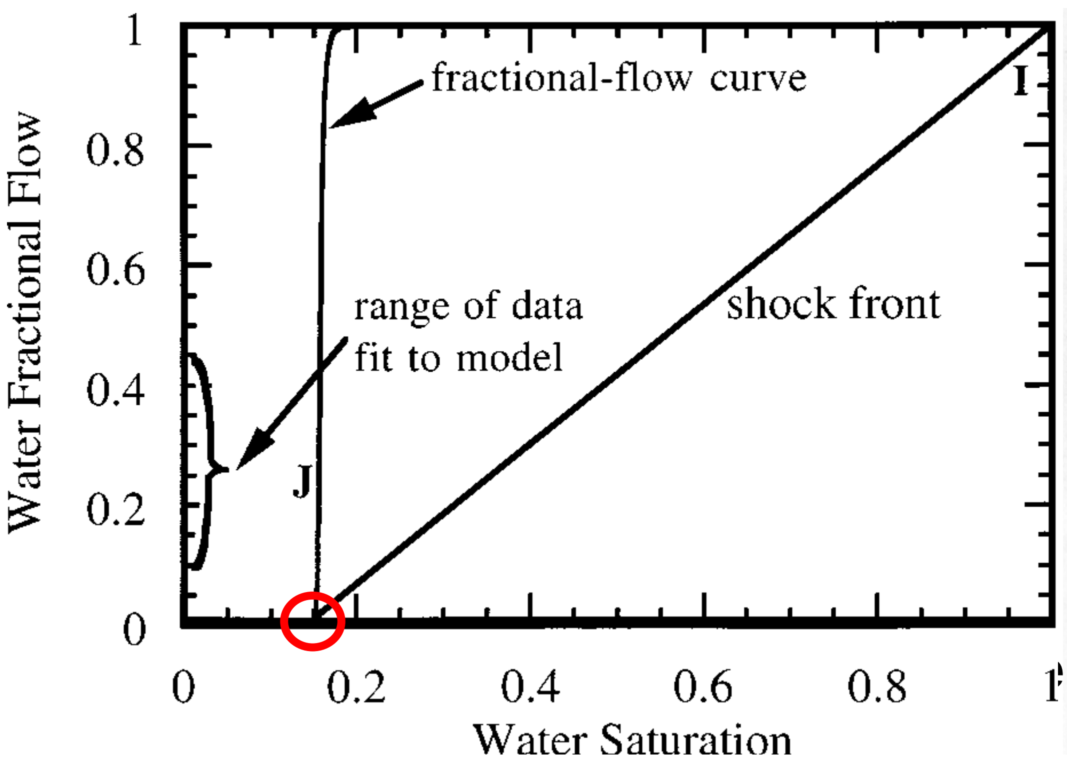
- Exists in two distinct regimes depending on "quality" (gas volume fraction)

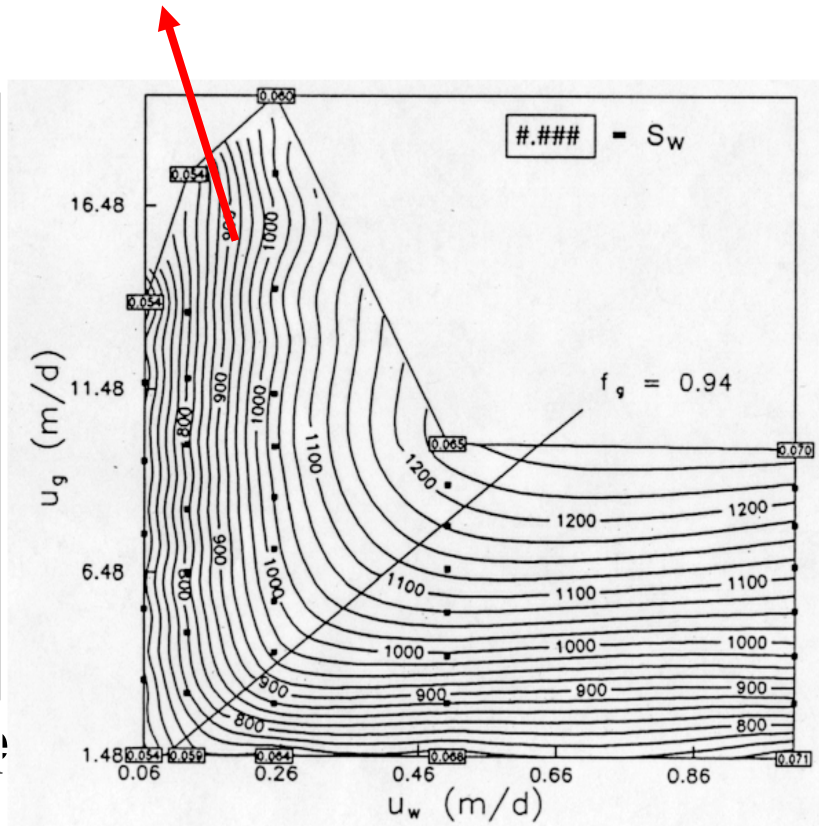


Transition between regimes depends on T, p, salinity, concentration + type of surfactant, formation permeability ...

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 CO_2, 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?

Key foam properties: Foam in Fractures

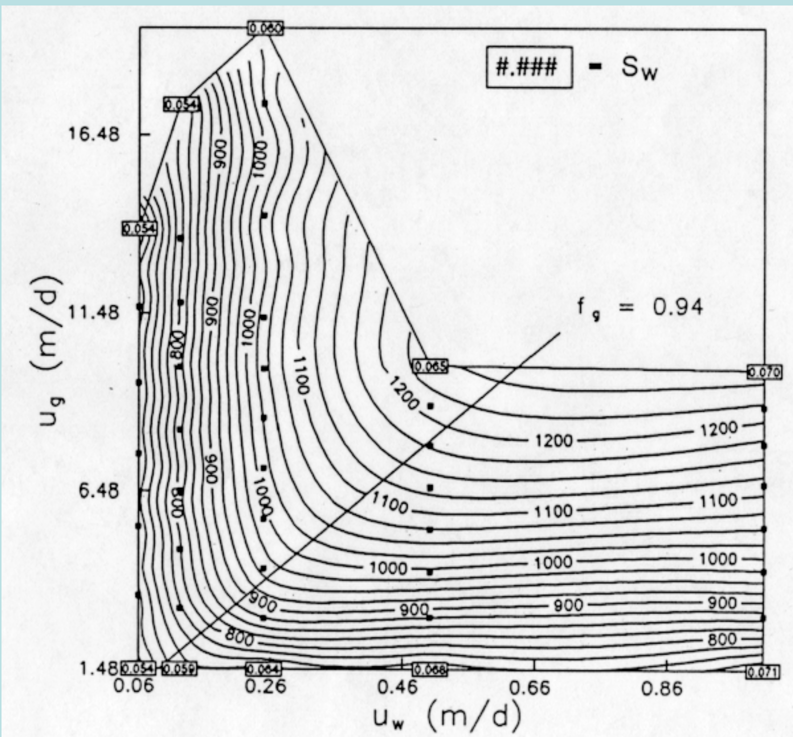
- *If* foam is present, it reduces gas channeling in fractures; but would foam form in fractures?
- Foam generation shown in lab in rough fractures 31 and 100 μm wide
- Foam generation less certain if fractures are too wide
- What happens to foam in vugs?
- Alternative: make a foam with cross-linked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

How Does Foam Help?

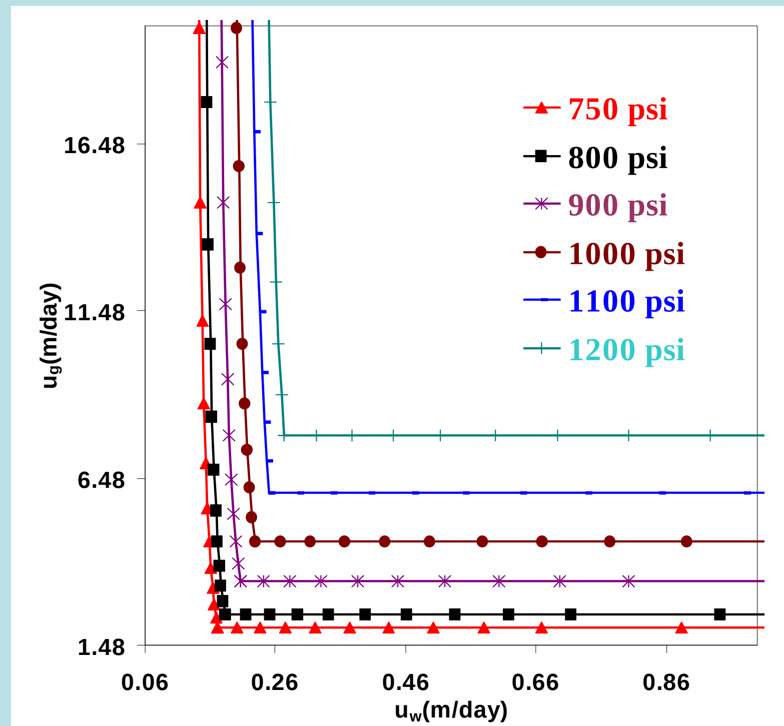
- Problems: reservoir heterogeneity, viscous instability, gravity override
- Heterogeneous formations: In "high quality regime," foam reduces mobility more in high-k layers; diverts flow to low-k layers
- Viscous instability*: All* foams reduce mobility
- Foam increases viscous pressure gradient in competition 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)



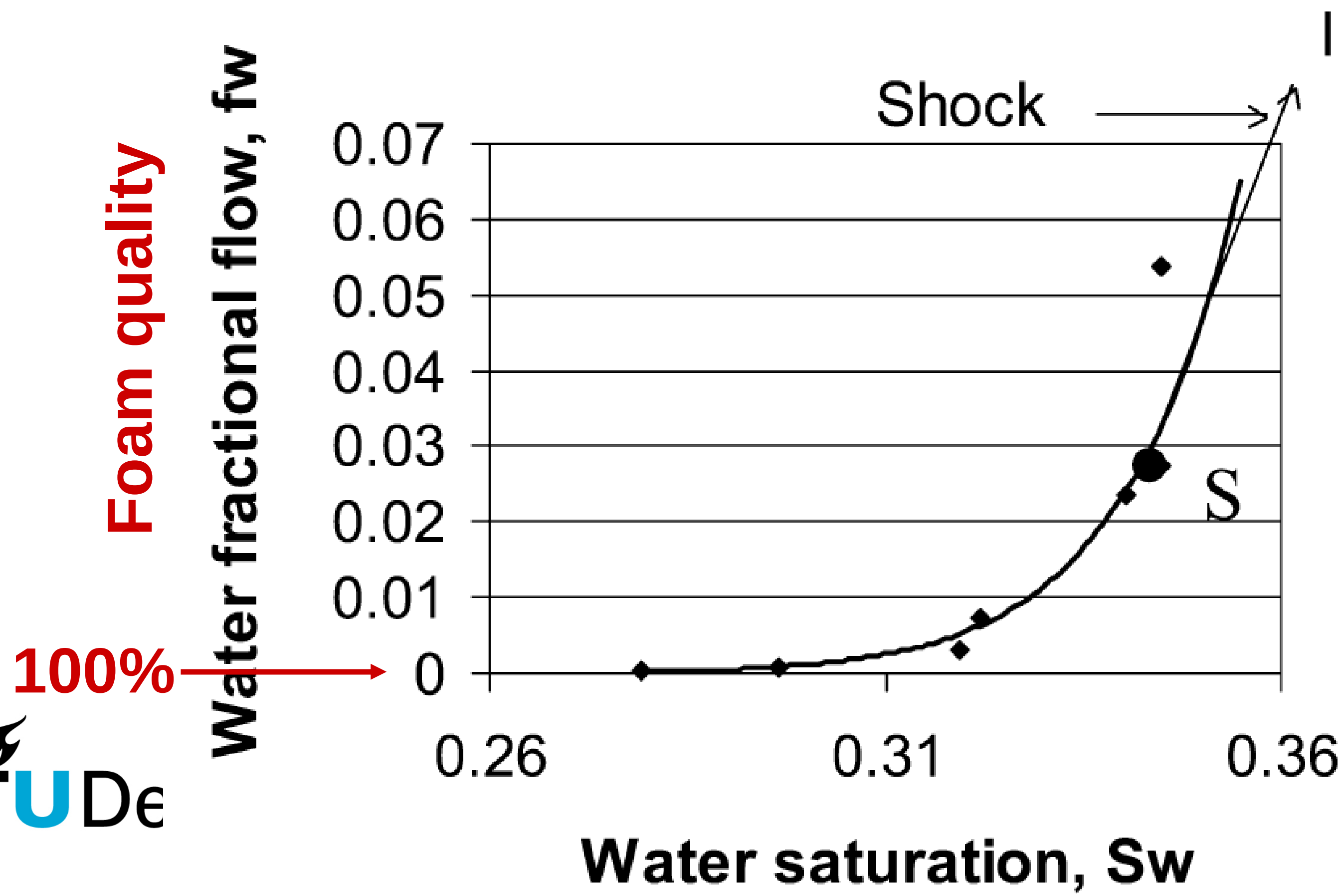
Data



Model Fit

Foam modeling and scale-up

- Need more data and modeling of behavior important to SAG processes
- Example study w/ N_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 ≥ 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