Studies of Foam for EOR and CO_2 storage: Liquid Injectivity[3], the Effect of Oil on Foam[2], and Generation In-situ in Heterogeneous Formations[1]

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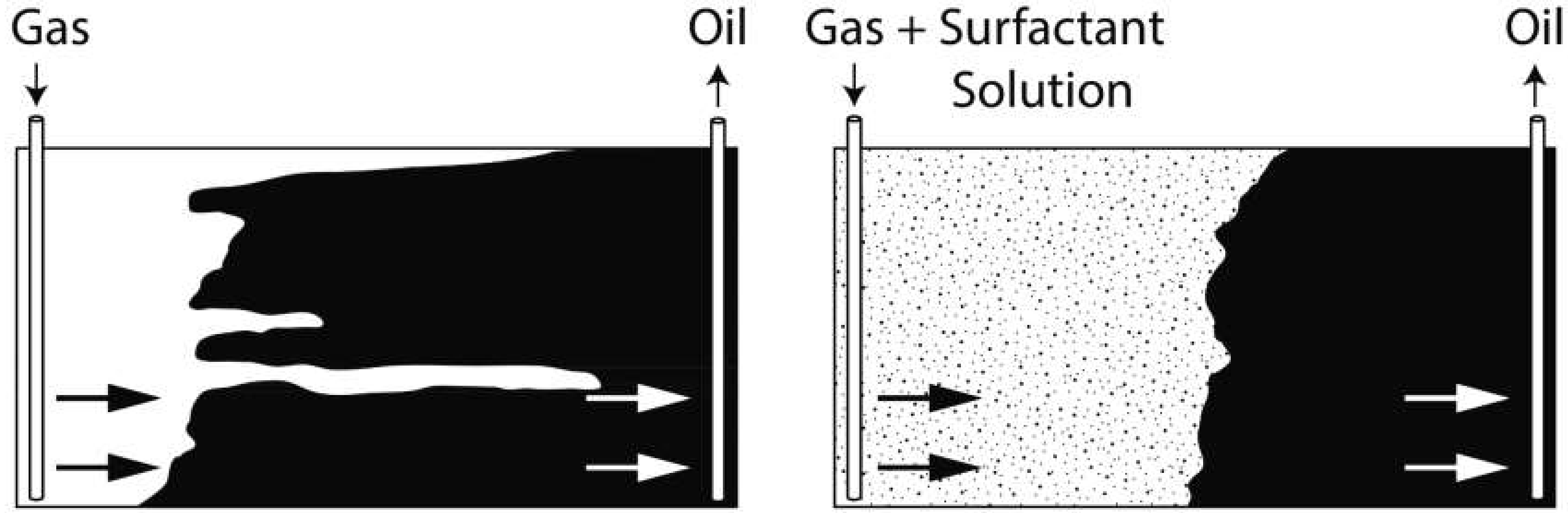
INTRODUCTION TO FOAM IN POROUS MEDIA

Subsurface applications

- ☐ Foams are a distribution of discontinuous gas bubbles in a continuous liquid phase.
- ☐ Gas mobility reduction, conformance improvement in displacement processes.
    - ▪ Enhanced oil recovery (EOR).
    - ▪ Shallow aquifer remediation - (D)NAPL removal.
    - ▪ CO_2 storage.



[1]Fried, A.N., 1961
[2]Marsden, 1986
[2]Kovscek and Radke, 1994
[3]Rossen, W.R., 1996
[4]Hirasaki, G.J. et. al., SPE J., 1997
[5]Alcorn, Z.P. et. al., 2018
[6]Rognmo, A. et. al. 2018

N_2 vs CO_2 FOAM

Some considerations before extending conclusions from N_2-foam to CO_2-foam:

☐ CO_2-water systems have lower interfacial tension

☐ CO_2 foam can be easier to generate

☐ Lower pressure gradient required to sustain propagation

☐ Different rates of gas diffusion.

☐ CO_2 solubility in water is much higher than N_2.

☐ Different behaviour in the presence of oil.

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Liquid Injectivity in Surfactant-Alternating-Gas Foam Enhanced Oil Recovery

- Injectivity is a key economic factor of a foam EOR process
  - ✓ Gas injectivity in SAG process is *good*
  - ✓ Liquid injectivity is often *very poor* in a SAG process

What controls liquid injectivity? How to model it?

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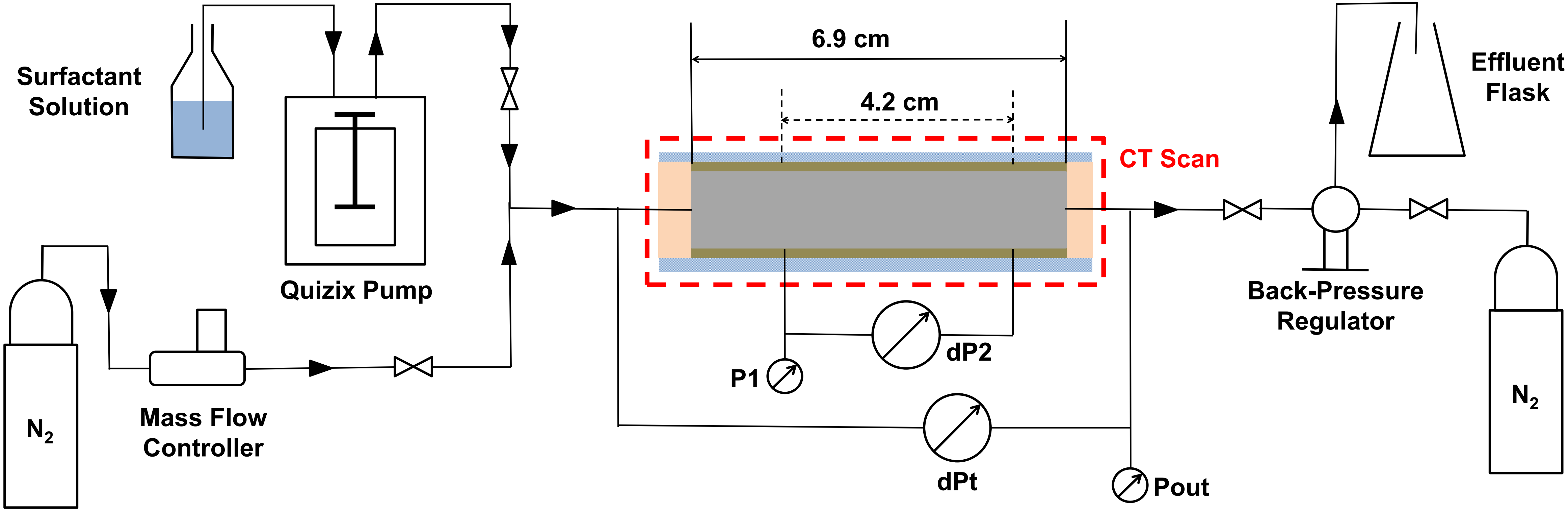
EXPERIMENTAL DESIGN



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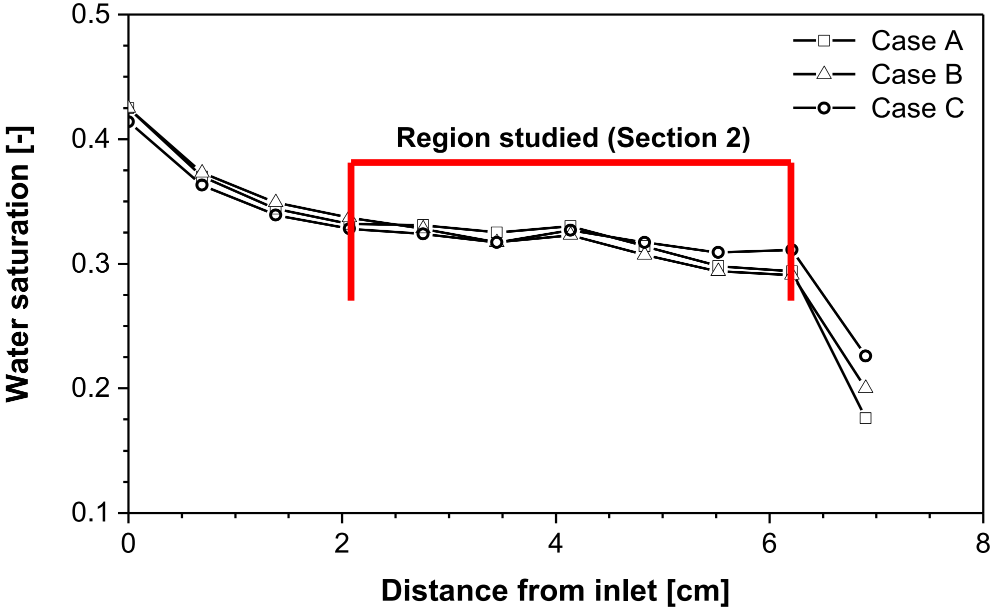
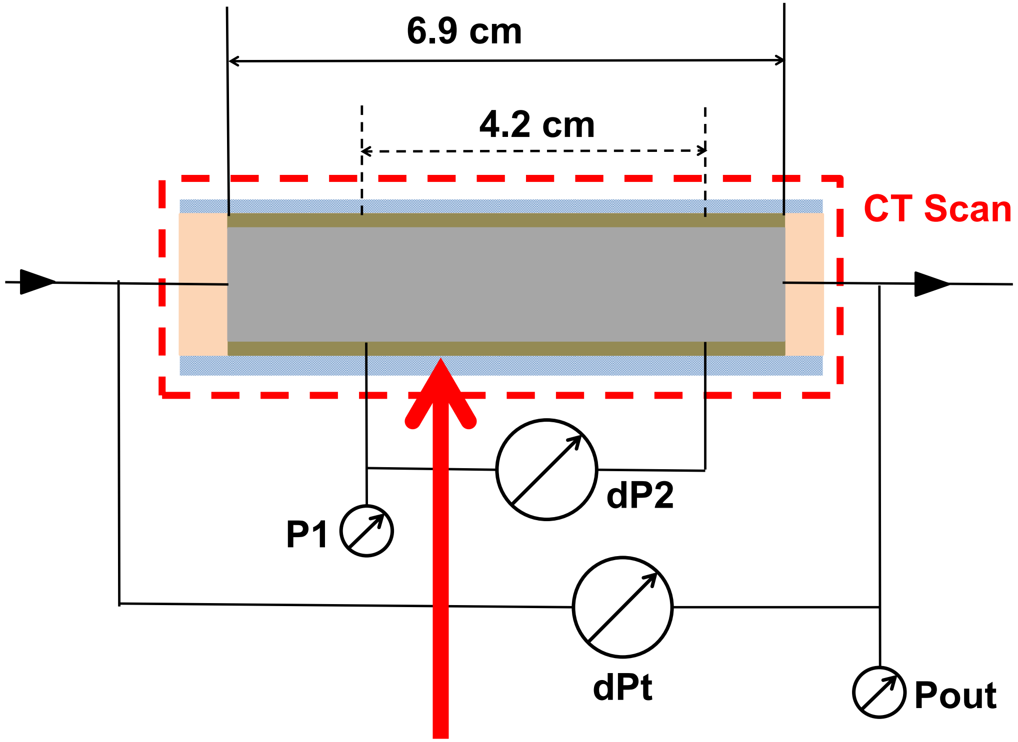
EXPERIMENTAL DESIGN





Field core is used for all experiments

Focus on middle section

Free of entrance and capillary-end effects

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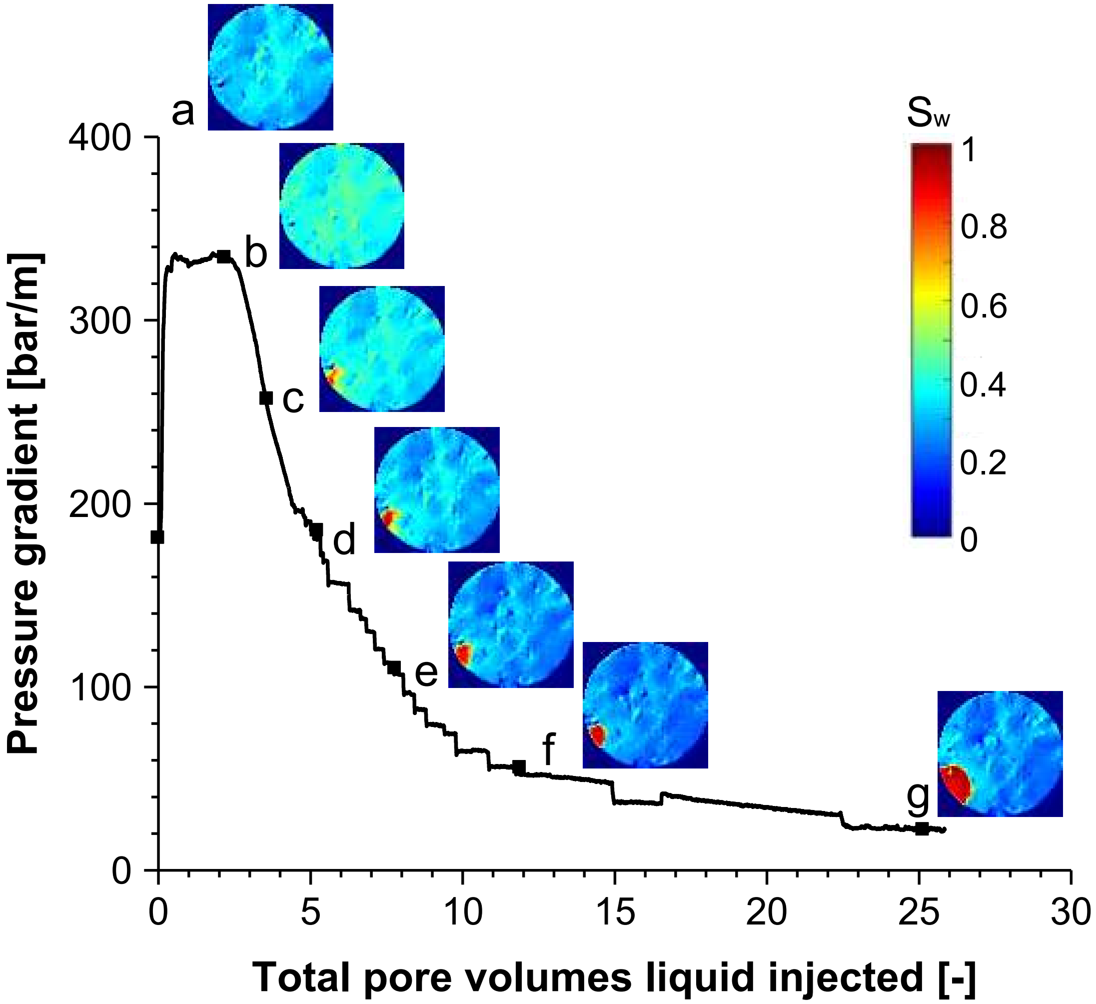
Liquid injection directly after steady-state foam

LIQUID INJECTION DIRECTLY AFTER STEADY-STATE FOAM



- Liquid injectivity directly following foam is poor
- Pressure gradient evolves over **three stages**
  - ✓ Liquid enters with relatively high mobility
  - ✓ Liquid penetrates foam in a finger
  - ✓ Displacement or dissolution of gas trapped within a finger into unsaturated injected liquid

Gong, J. et. al., EAGE IOR, 2019

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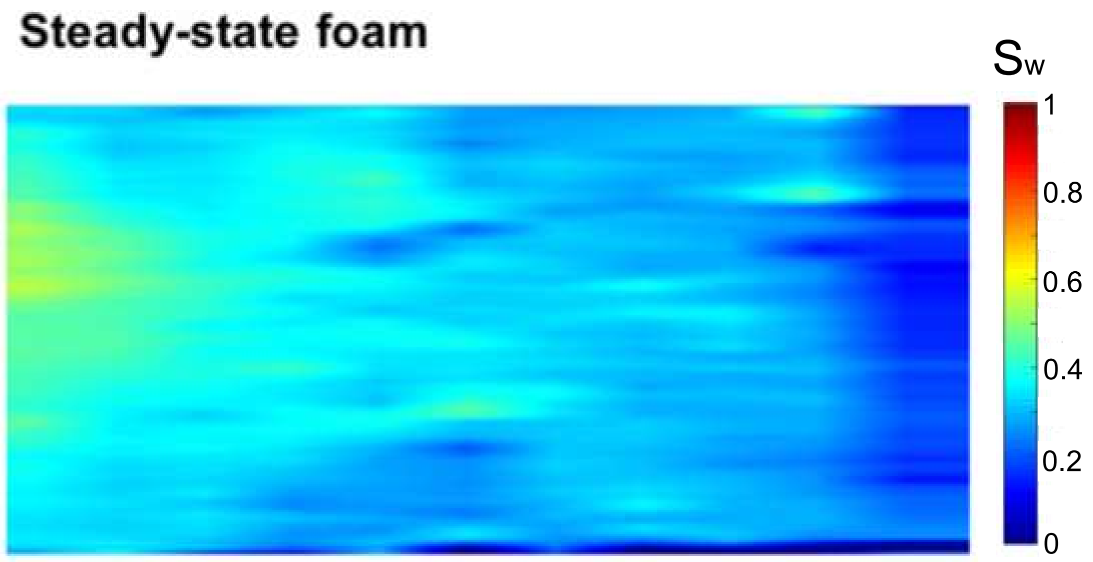
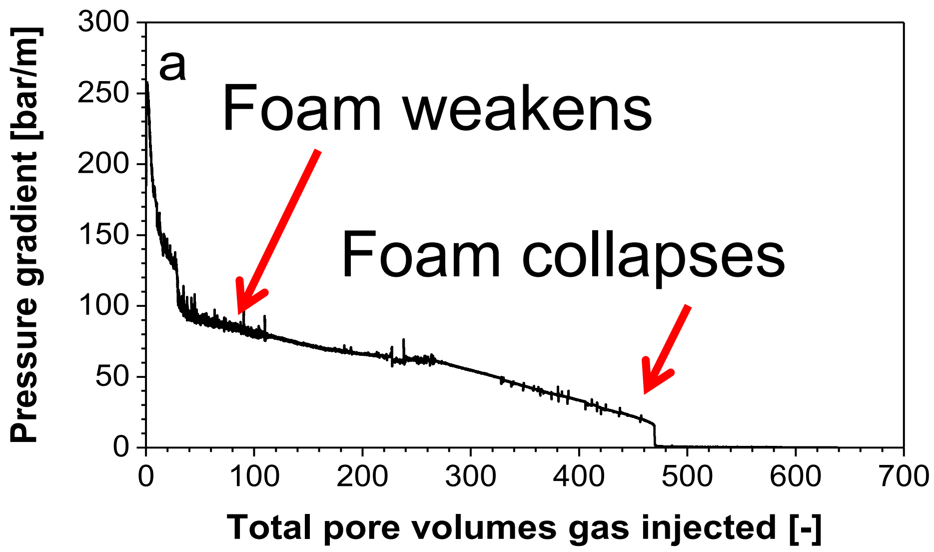
How would gas-slug injection affect subsequent liquid injectivity?

PROLONGED PERIOD OF GAS INJECTION

- The collapsed-foam region moves as a front from the inlet to the outlet as more gas is injected.
- Foam collapses or greatly weakens when a sufficient volume of gas is injected.





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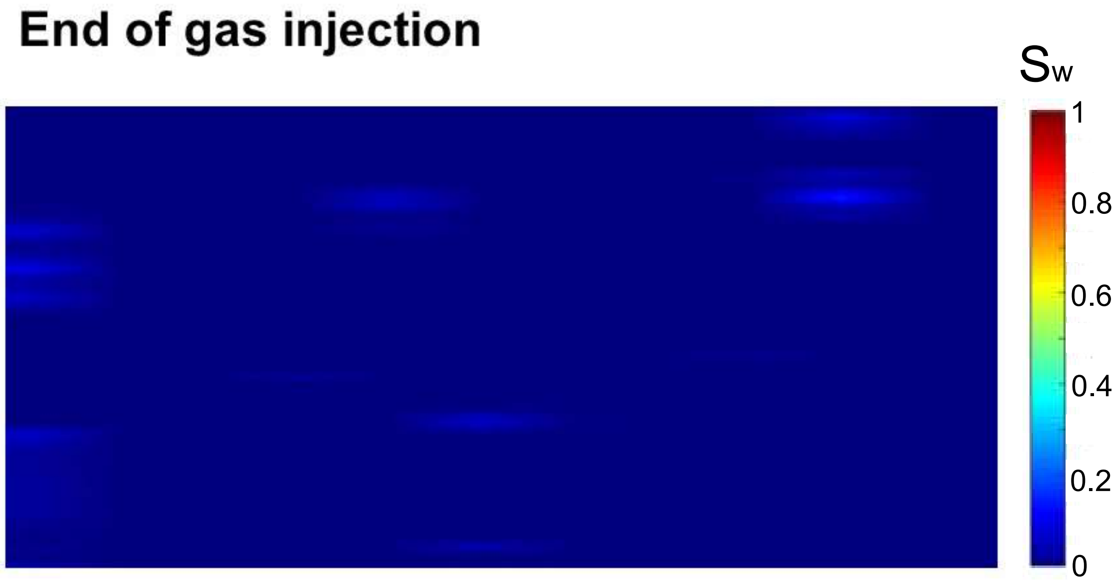
LIQUID FOLLOWS PROLONGED PERIOD OF GAS INJECTION



Liquid sweeps the entire cross section without fingering

- Foam collapses or greatly weakens after a prolonged period of gas injection, leaving less trapped gas
- Subsequent liquid injection is much easier than following full-strength foam

Gong, J. et. al., EAGE IOR, 2019

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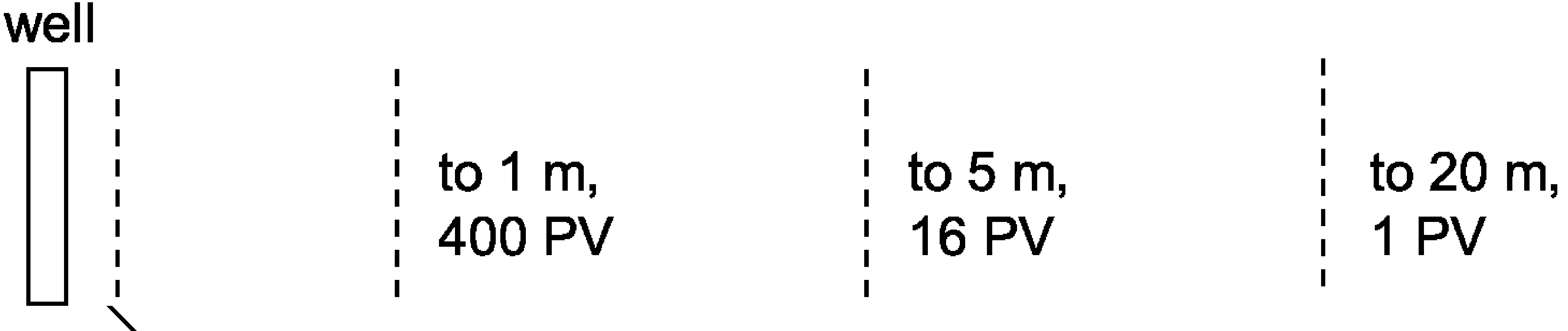
LIQUID FOLLOWS PROLONGED PERIOD OF GAS INJECTION

- Translate to radial flow

  If the gas slug in a SAG process is equivalent to the pore volume to a radius of 20 m from the well (far less than a pattern pore volume), at the end of injection of the gas slug ...



well

to 1 m,
400 PV

to 5 m,
16 PV

to 20 m,
1 PV

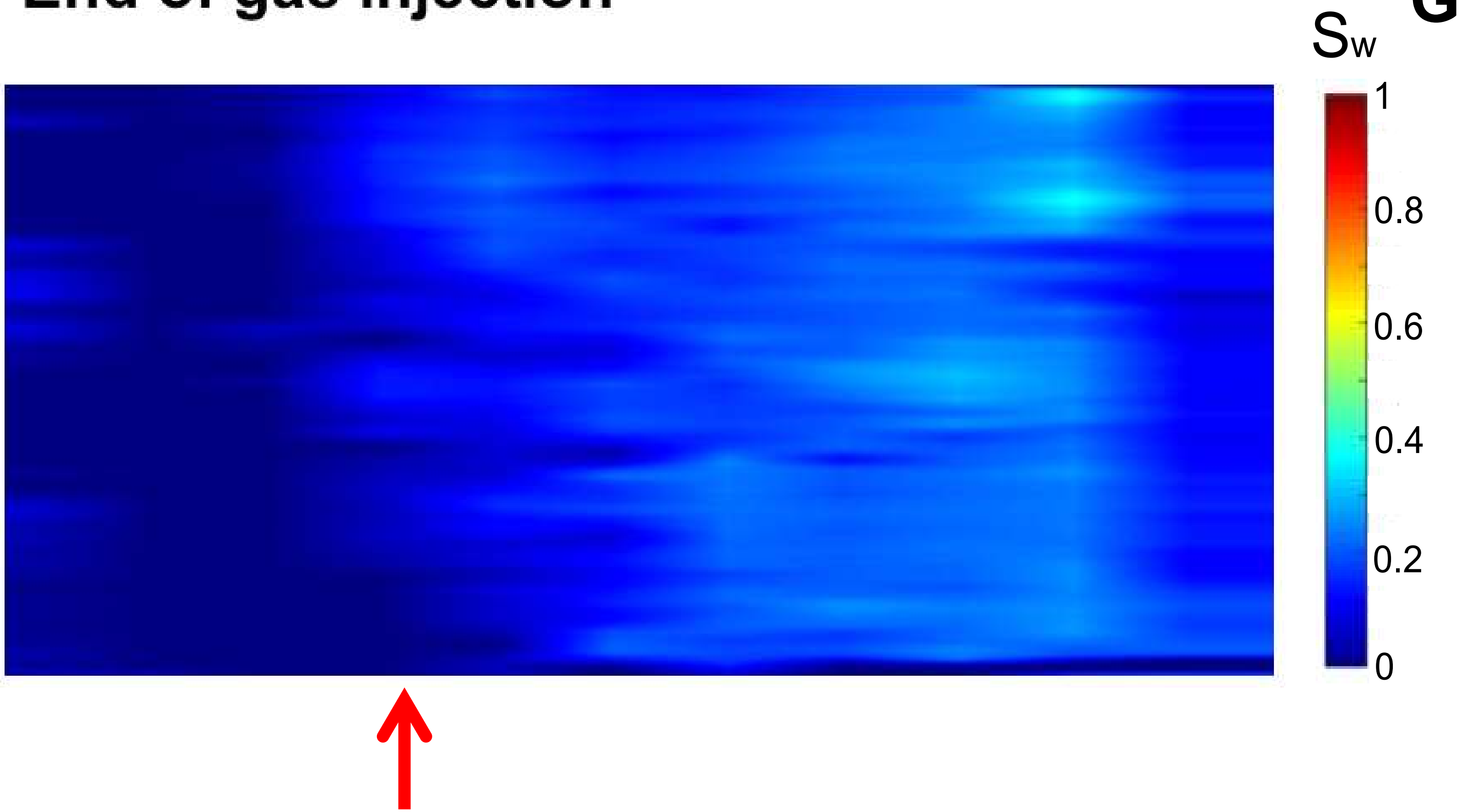
region out to 20 cm has seen
10,000 PV gas injection

In radial flow, radius out to 3 m represents half the pressure drop in a region of radius 100 m

LIQUID FOLLOWS A SMALLER GAS SLUG

End of gas injection

Gas-slug size: 250 PV



Foam collapses or greatly weakens to this position

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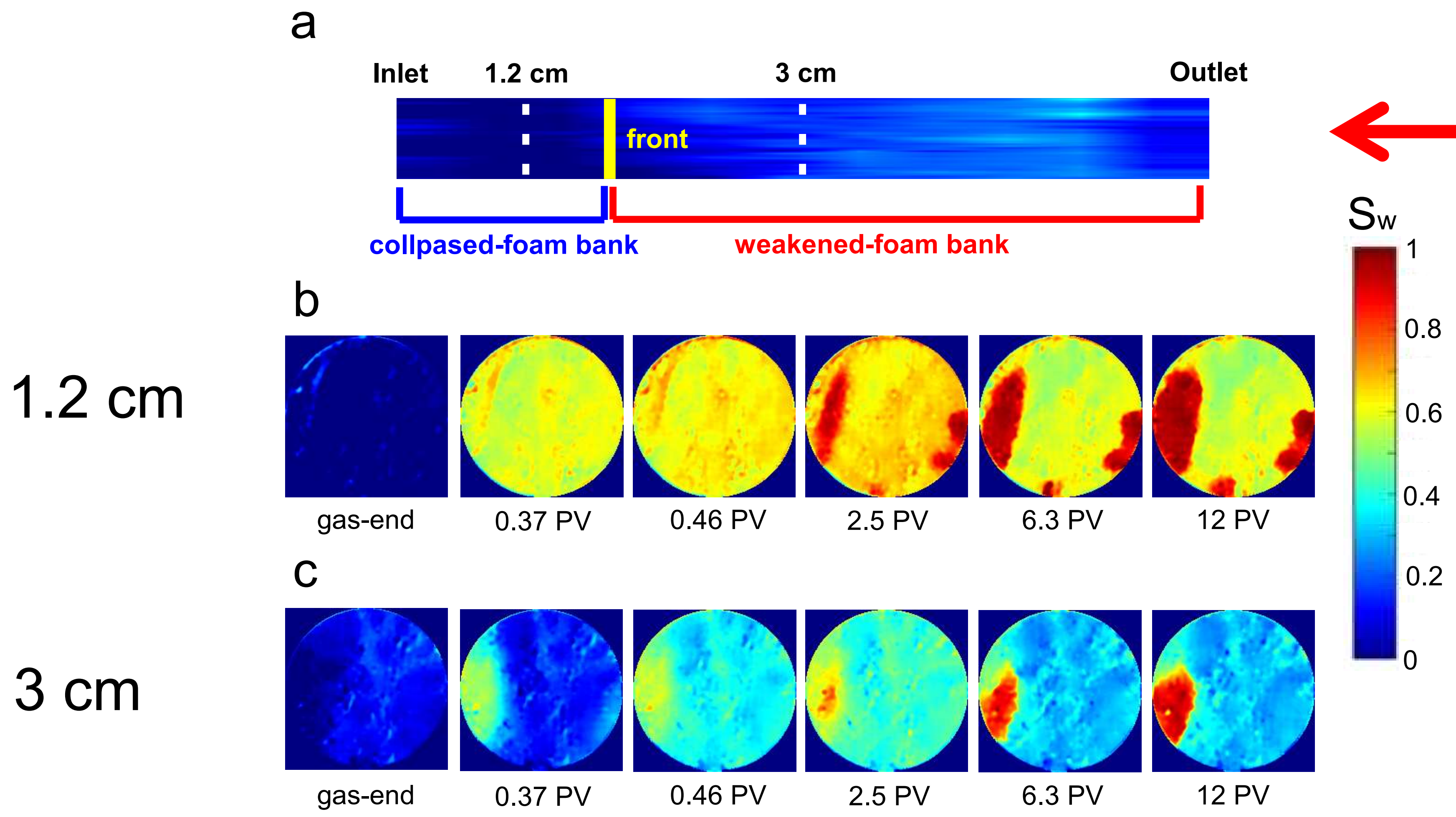
LIQUID FOLLOWS A SMALLER GAS SLUG



At the end of gas injection, core is occupied by the collapsed-foam bank and the weakened-foam bank

Gong, J. et. al., EAGE IOR, 2019

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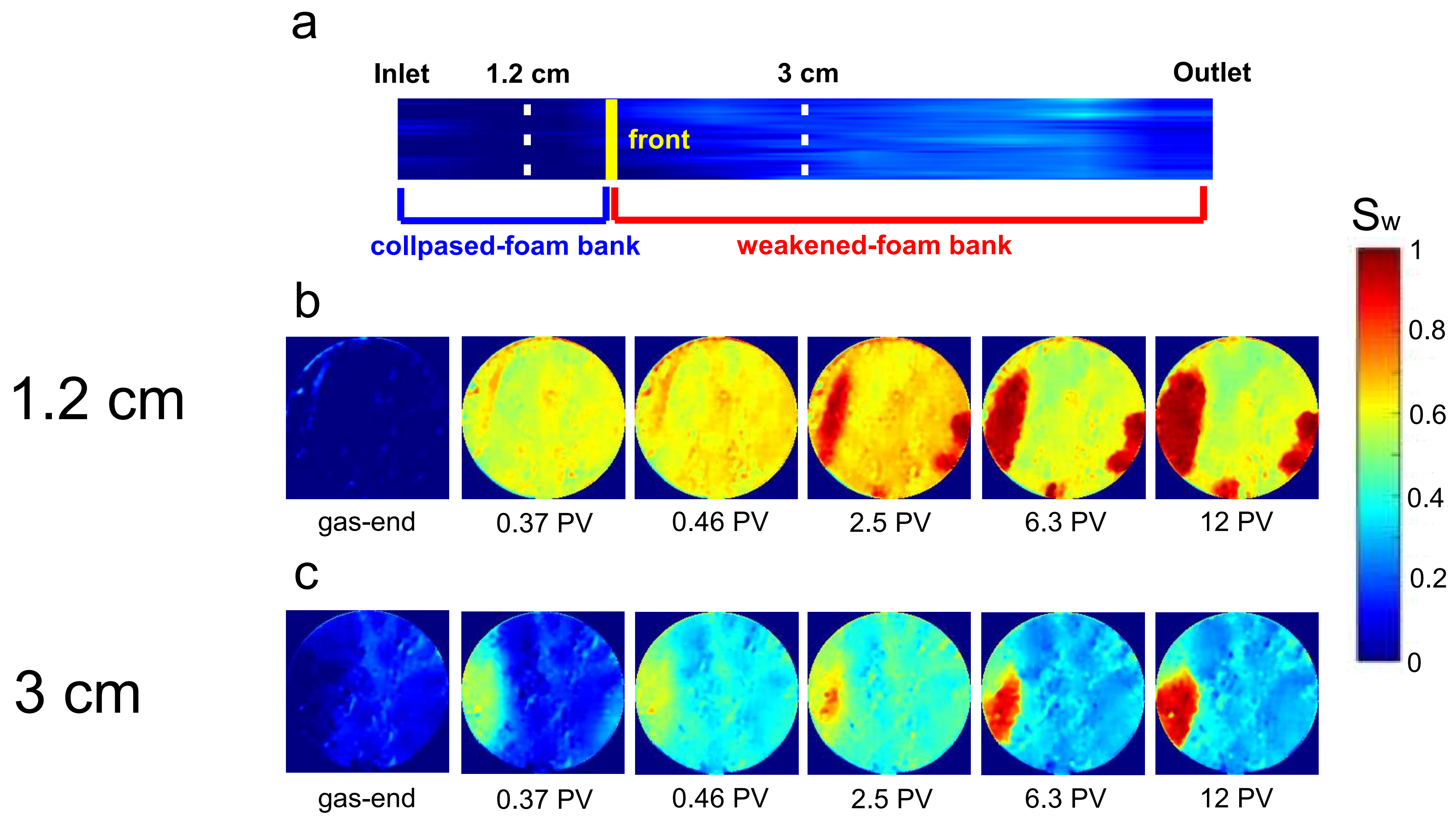
LIQUID FOLLOWS A SMALLER GAS SLUG



In the collapsed-foam region, liquid first flushes the entire cross section, then forms preferential paths

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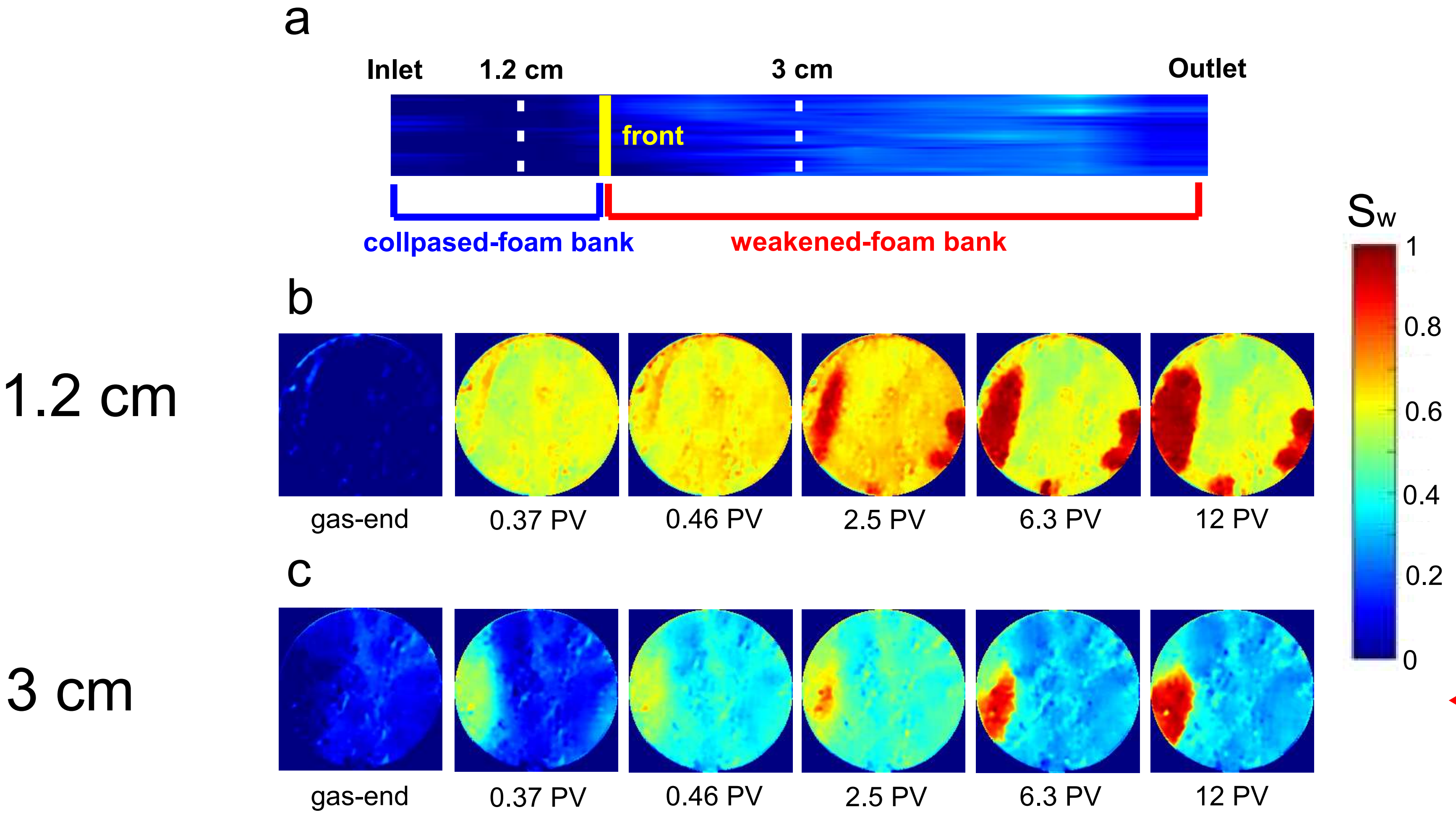
LIQUID FOLLOWS A SMALLER GAS SLUG



In the weakened-foam region, liquid fingers through foam as in liquid injection directly following foam

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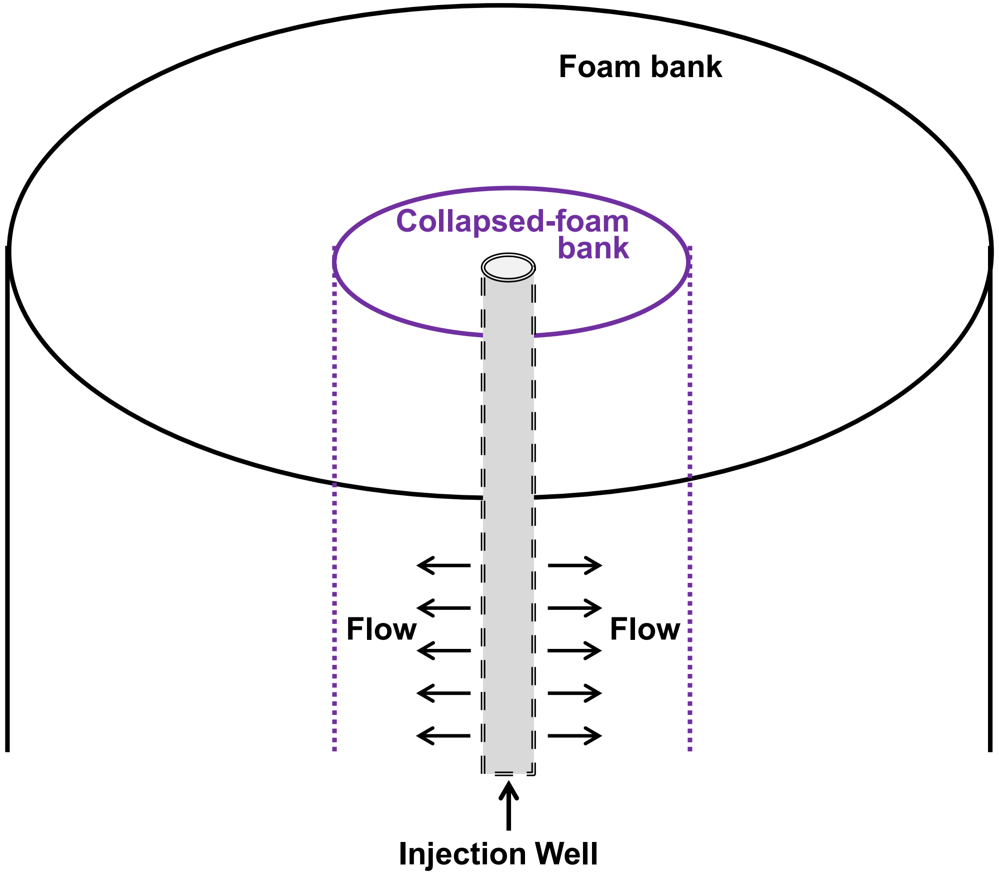
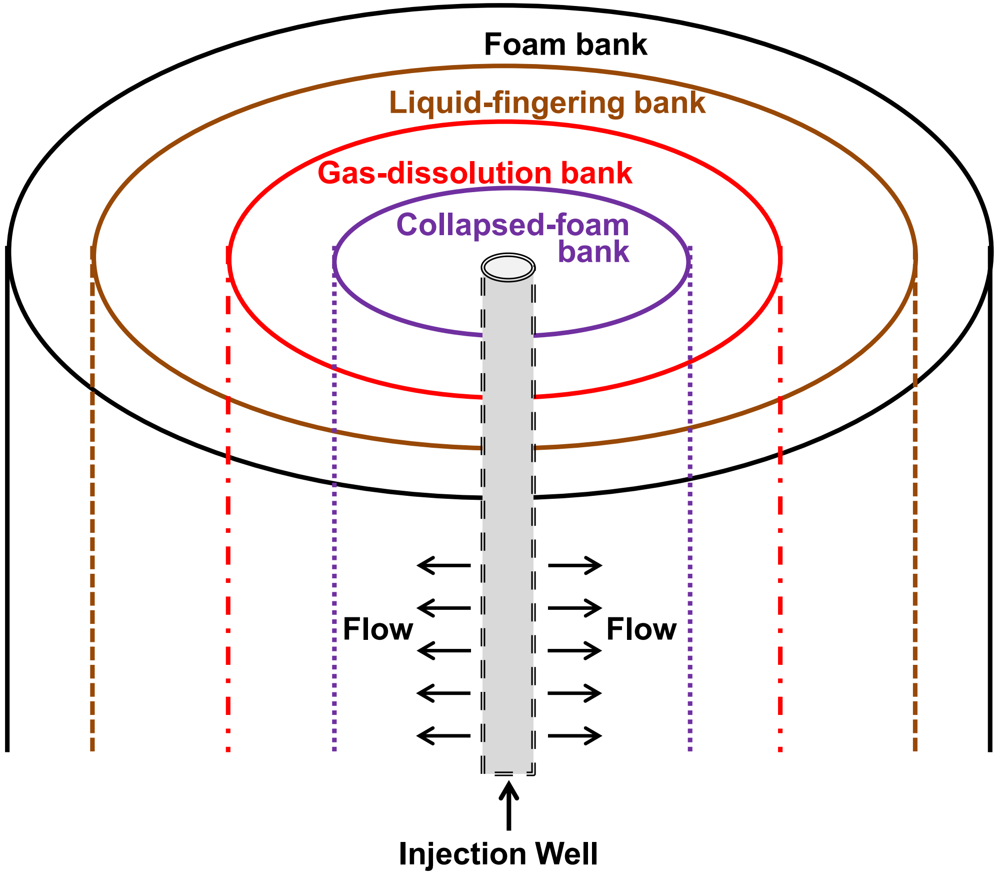
Bank-propagation model

BANKS IN A SAG PROCESS



Gas-injection period



Liquid-injection period

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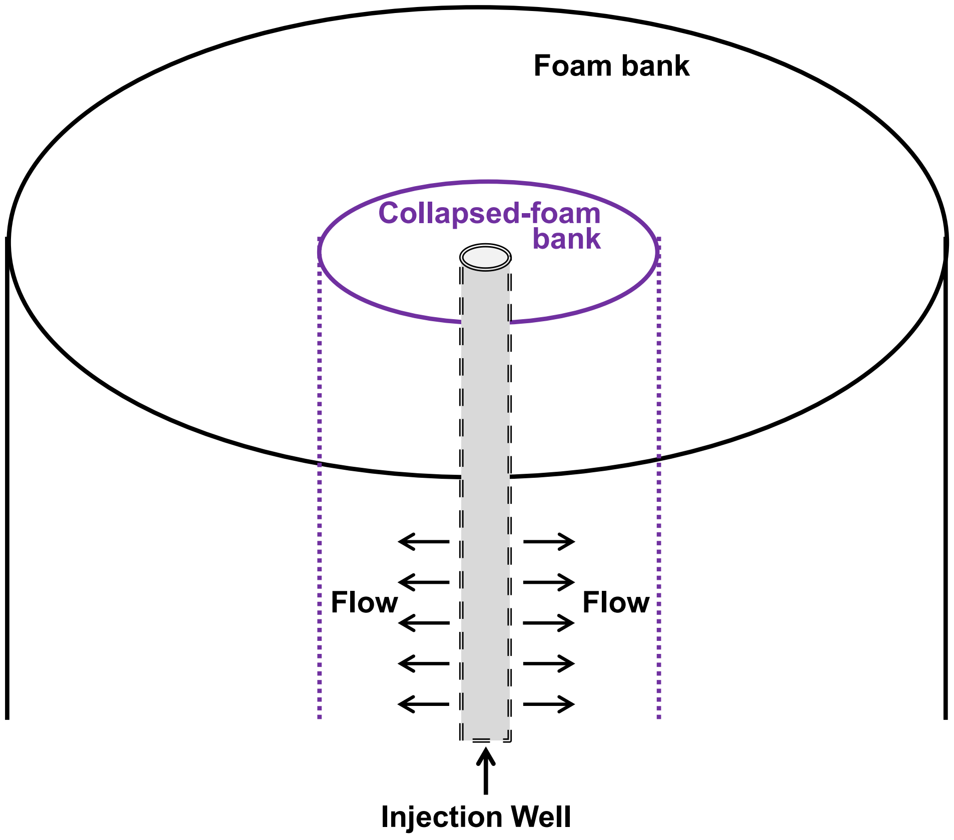
BANK-PROPAGATION MODEL

Gas-injection period:



total pressure difference

$$\Delta p_t = \Delta p_F + \Delta p_{FCG}$$

foam bank

collapsed-foam bank

Key parameters:

Dimensionless propagation velocity

Total mobility of each bank

Gong, J. et. al., SPE J., 2019

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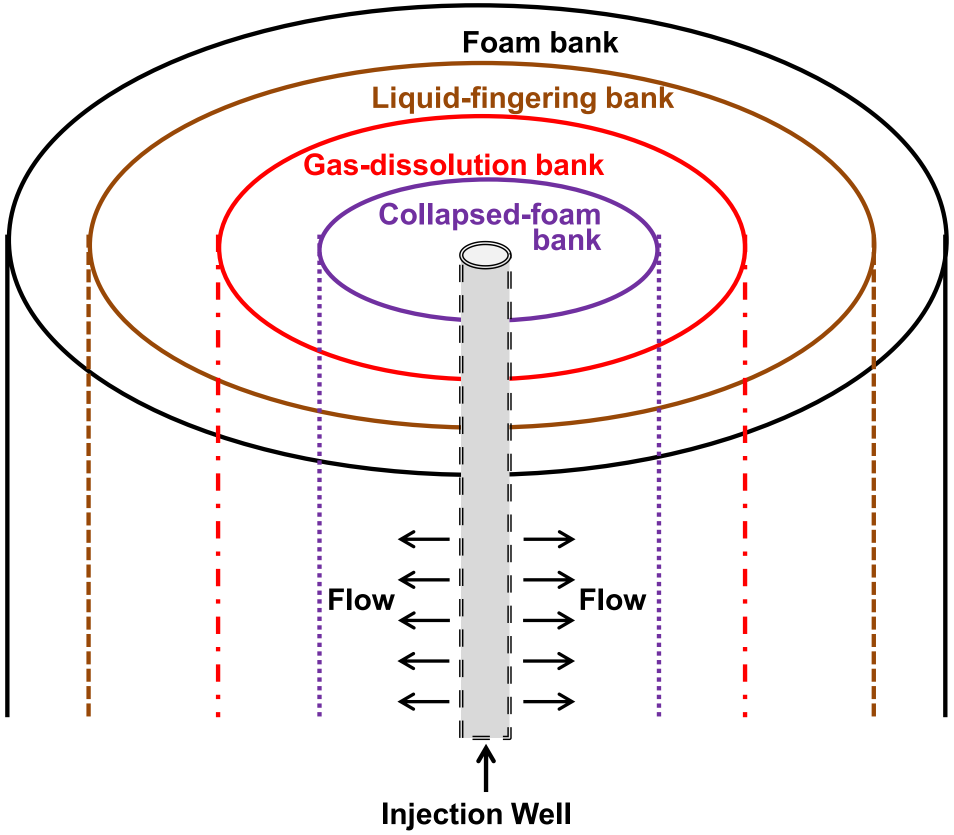
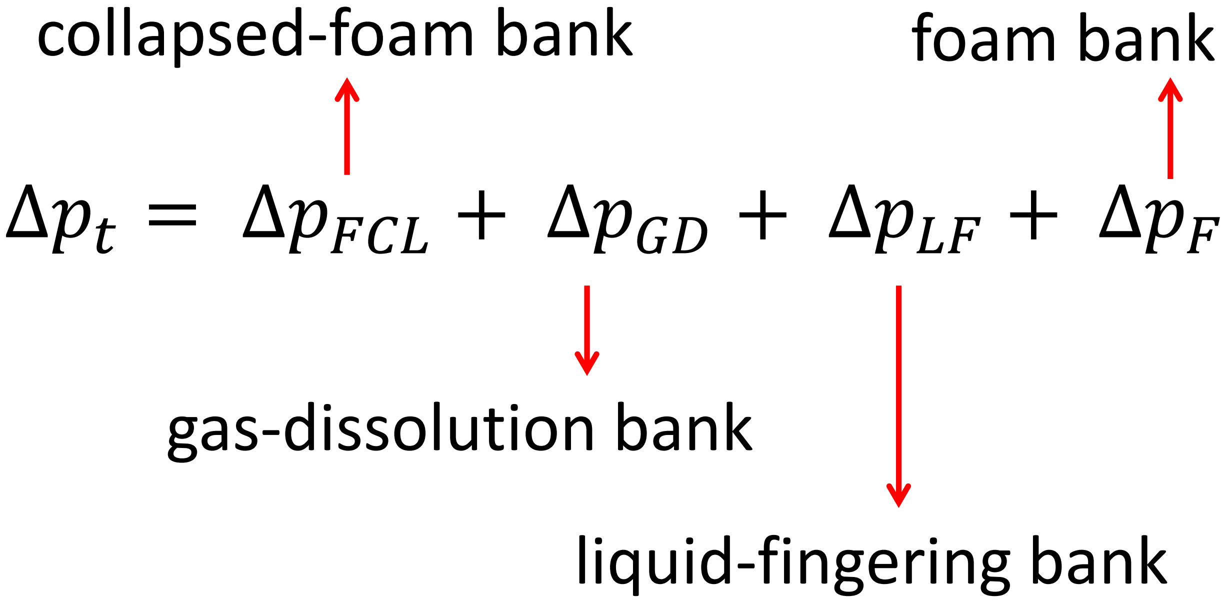
BANK-PROPAGATION MODEL

Liquid-injection period:




collapsed-foam bank

foam bank

$$\Delta p_t = \Delta p_{FCL} + \Delta p_{GD} + \Delta p_{LF} + \Delta p_F$$

gas-dissolution bank

liquid-fingering bank

Solve Darcy's Law in each bank

Gong, J. et. al., SPE J., 2019

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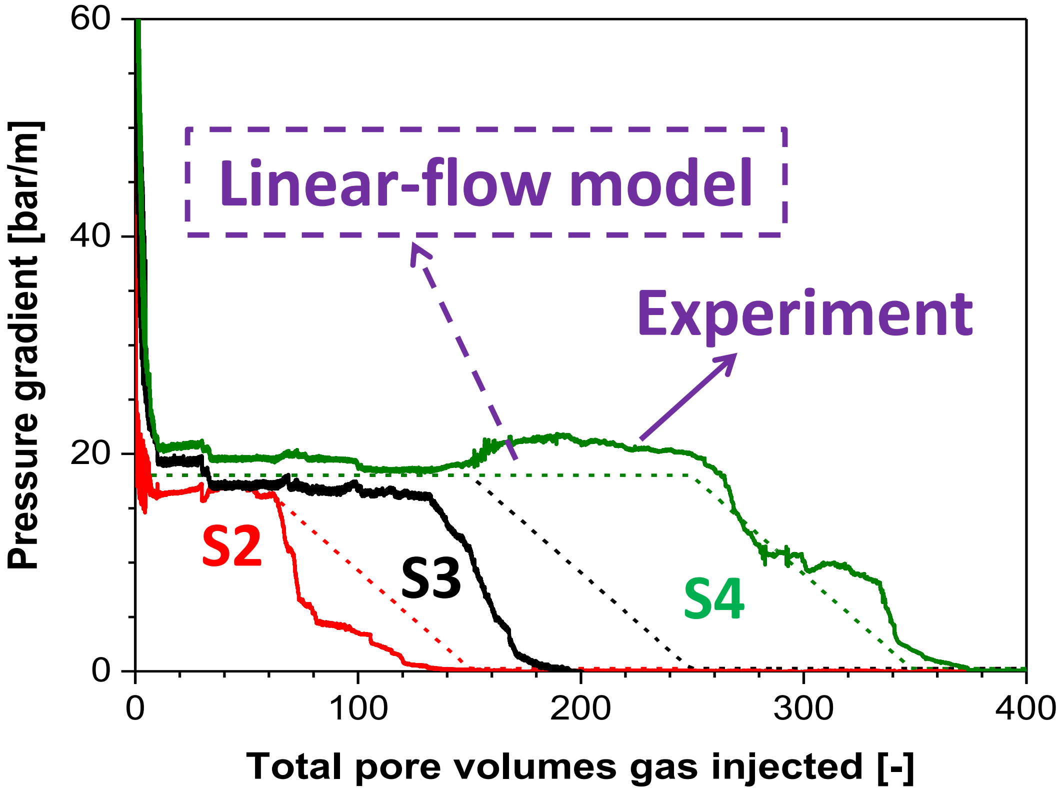
LINEAR-FLOW FIT FOR GAS INJECTIVITY



- Linear-flow model gives reasonable fit to lab data. Especially **Section 4.**
- In **Sections 2 and 3**, foam collapse takes a somewhat shorter time in experiment than in model.

WHY?

- Drying out and collapse of foam reflects interplay of pressure gradient, capillary effects, evaporation.
- Not all of these effects scale-up simply.

Gong, J. et. al., SPE J., 2019

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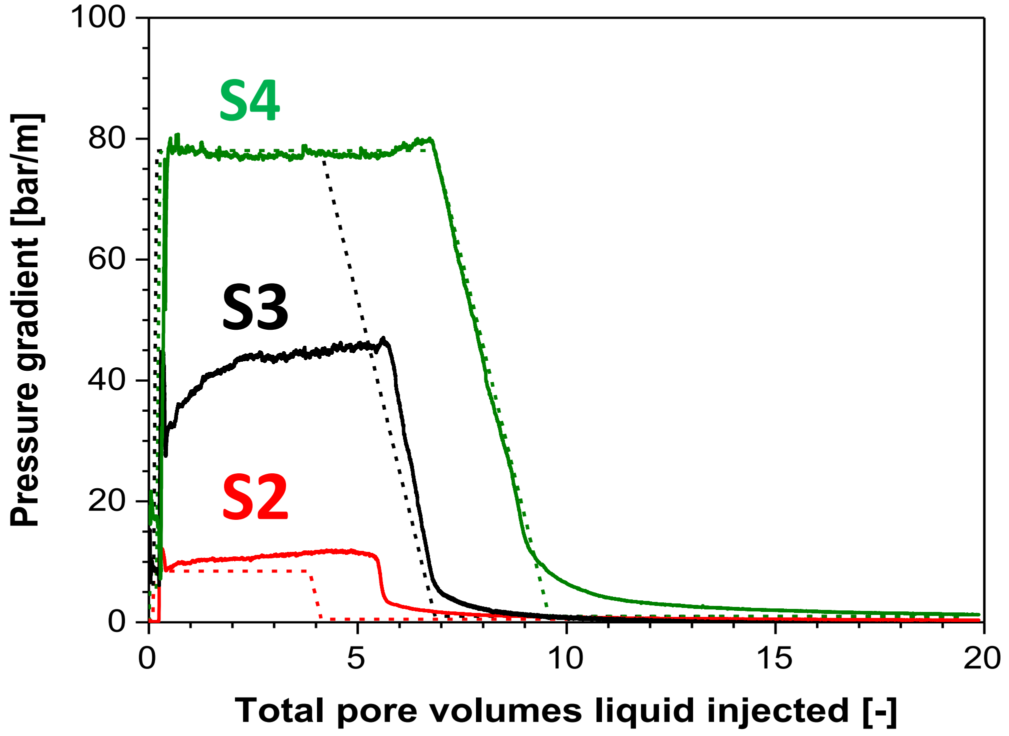
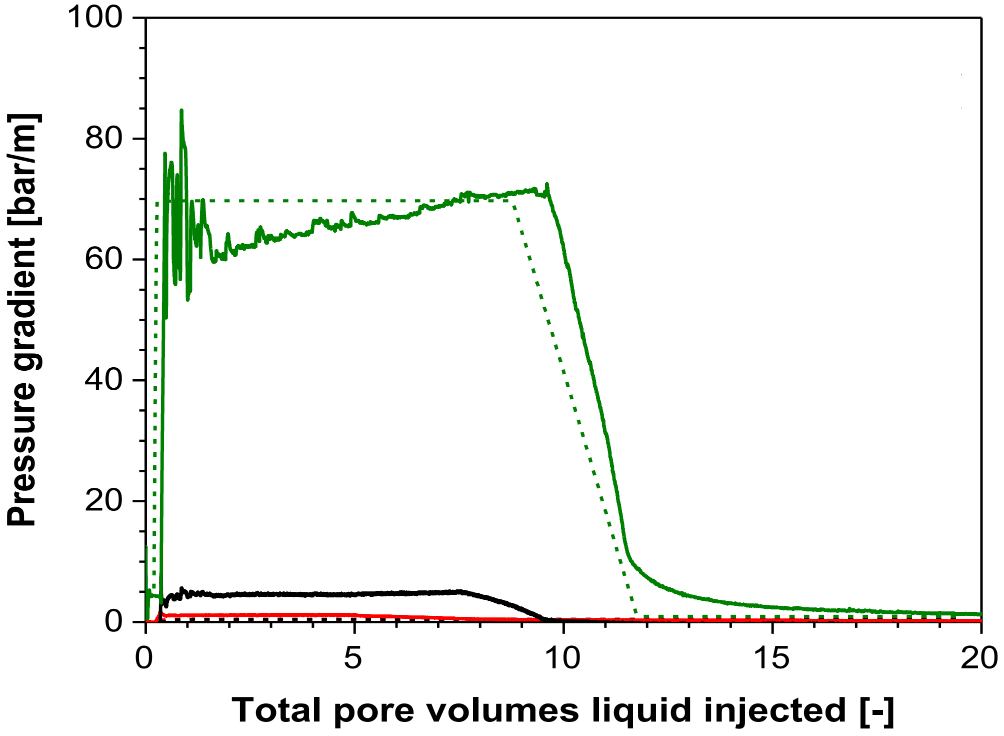
LINEAR-FLOW FIT FOR LIQUID INJECTIVITY



Liquid injection follows ***135 TPV*** gas



Liquid injection follows ***245 TPV*** gas

Linear-flow model gives reasonable fit to lab data

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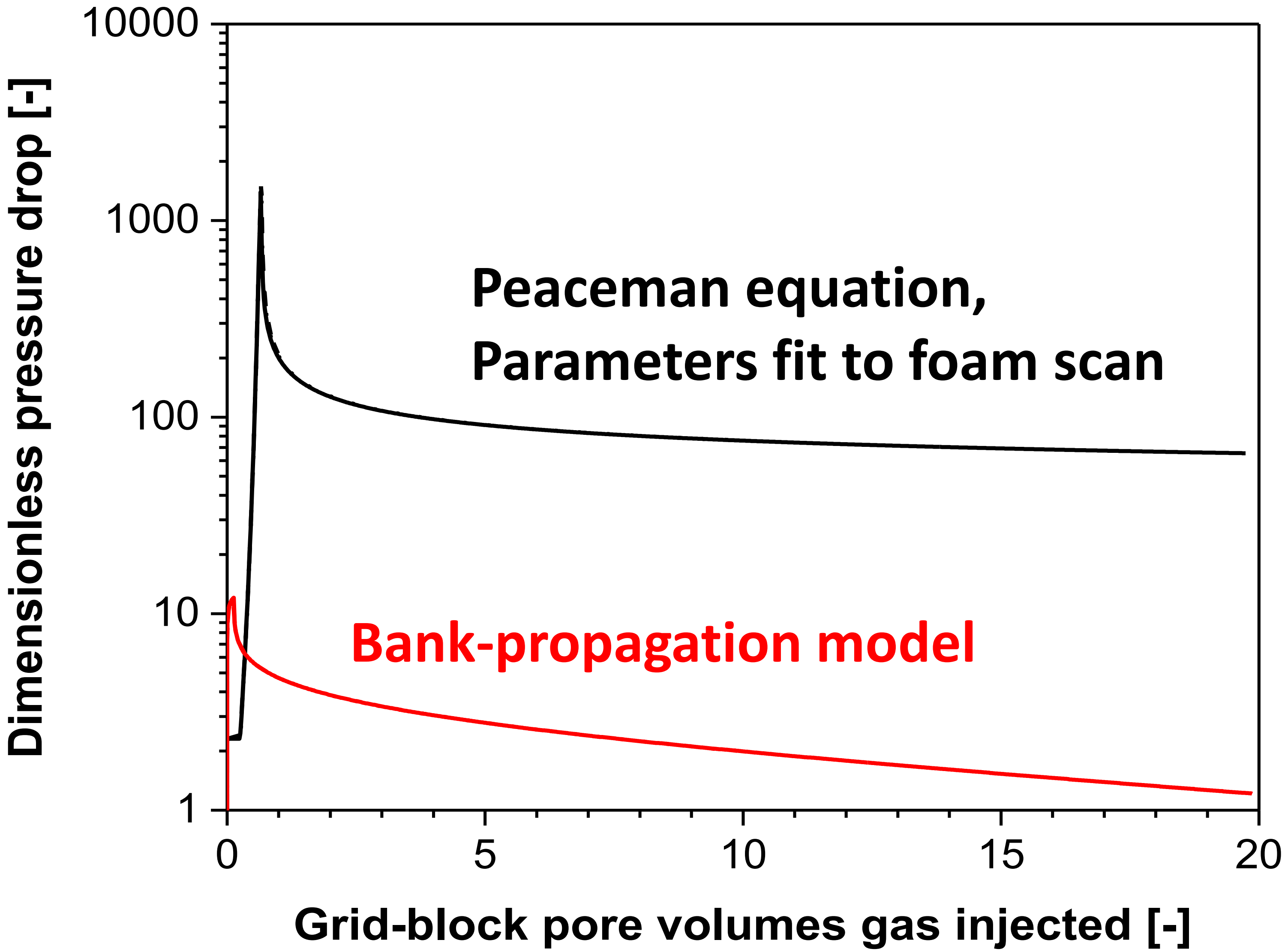
Can conventional foam simulators represent our experimental findings?

PEACEMAN EQUATION VS. BANK-PROPAGATION MODEL

GAS INJECTIVITY



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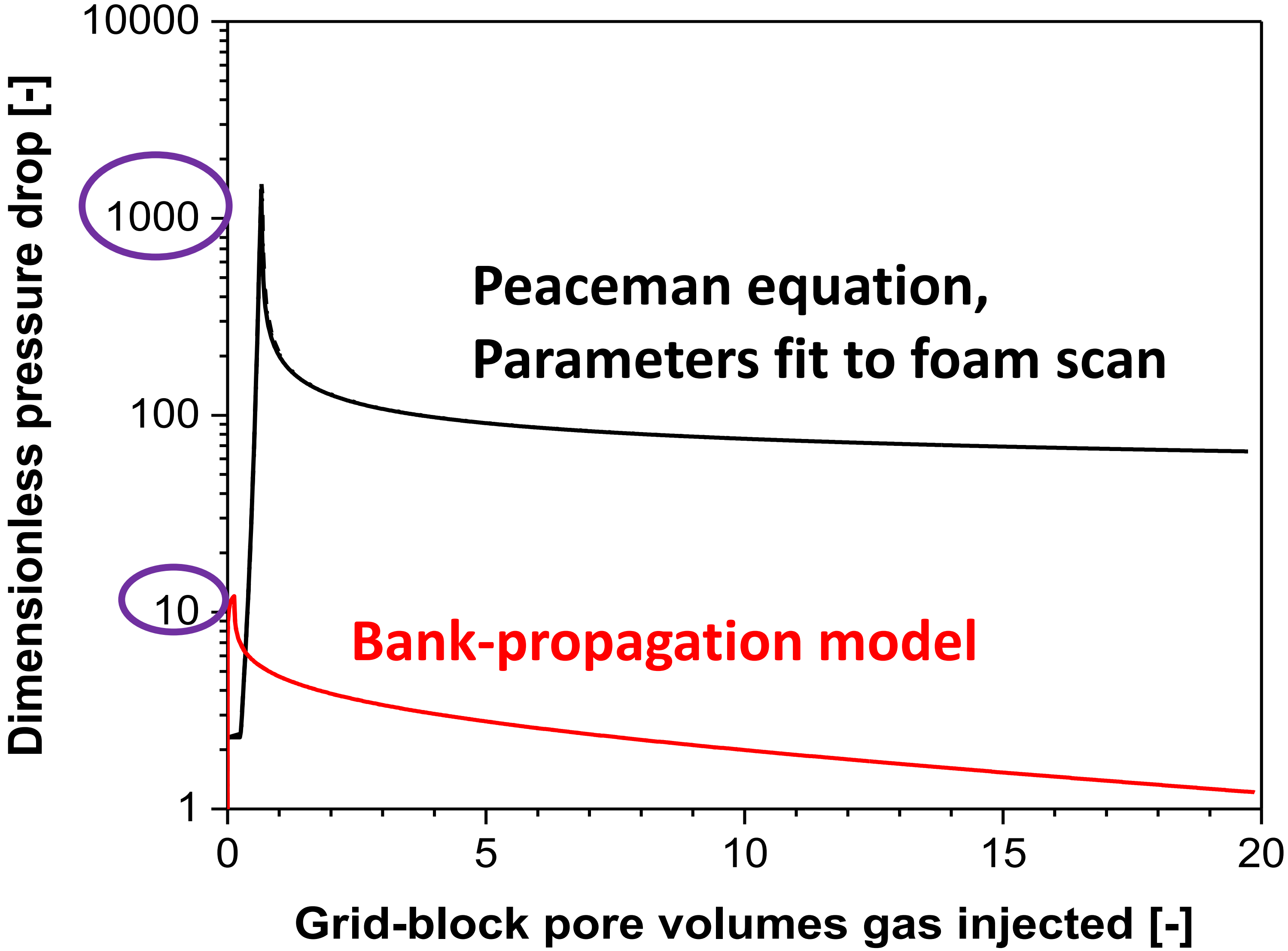
PEACEMAN EQUATION VS. BANK-PROPAGATION MODEL

GAS INJECTIVITY



Peaceman equation based simulation overestimates pressure peak by *70* times.

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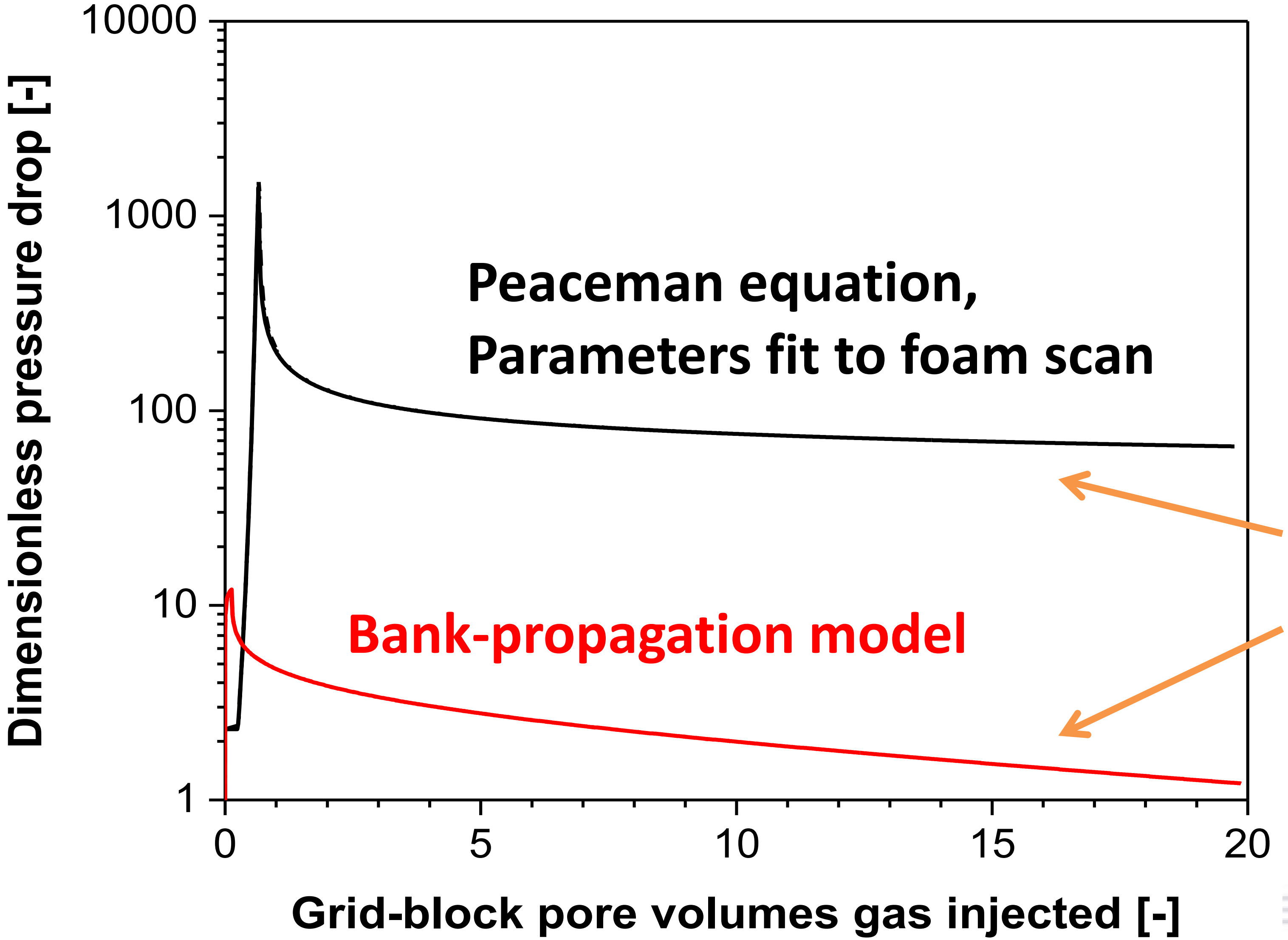
PEACEMAN EQUATION VS. BANK-PROPAGATION MODEL



Peaceman equation based simulation overestimates pressure rise by *40* times at a later stage.

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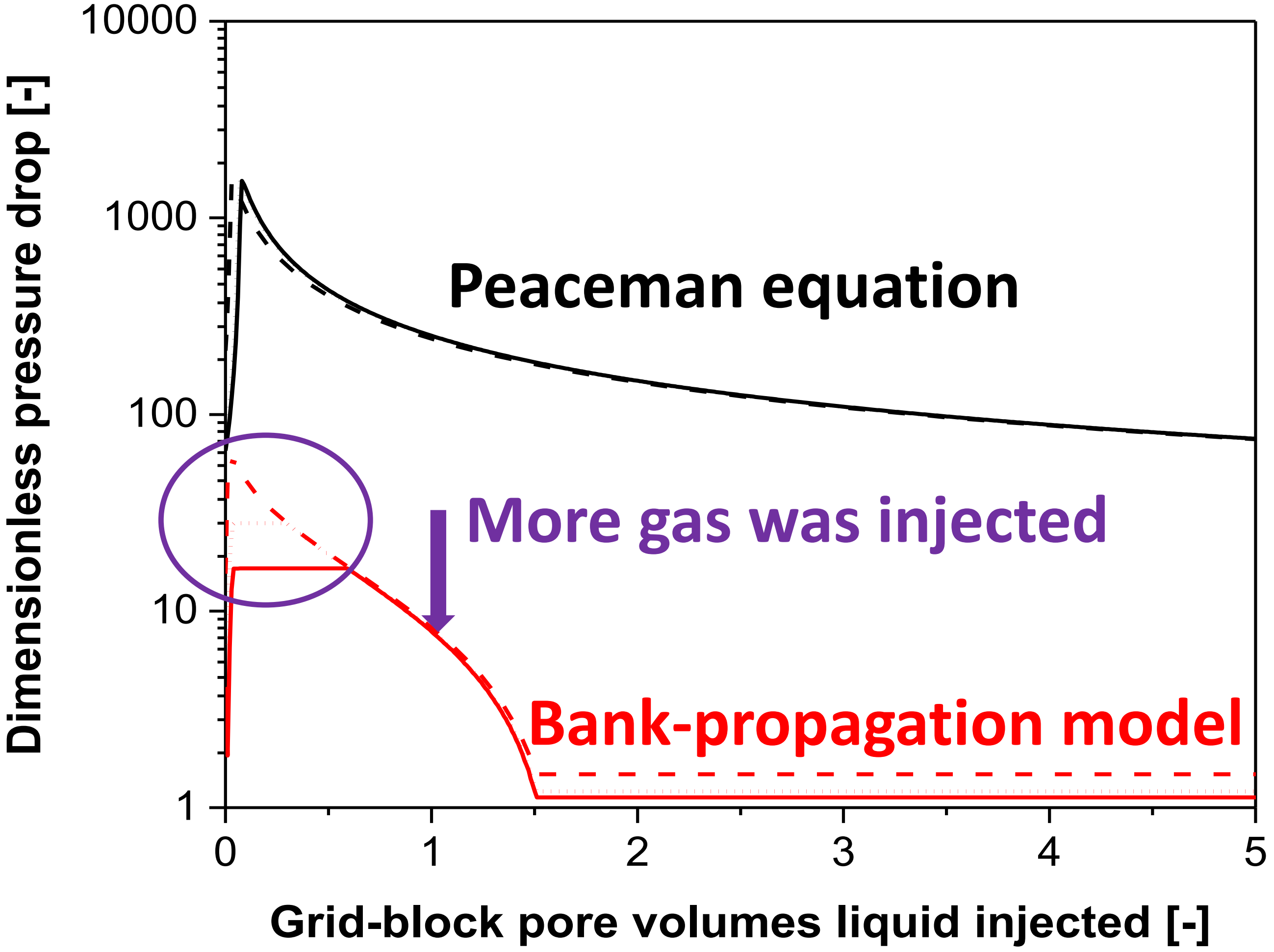
PEACEMAN EQUATION VS. BANK-PROPAGATION MODEL

LIQUID INJECTIVITY



- In radial-flow calculations based on lab data, larger gas slugs increase injectivity of liquid slugs.
- **Small effects of gas slug on subsequent liquid slug in Peaceman equation.**
- The more gas is injected before liquid, the bigger error the simulation would give.

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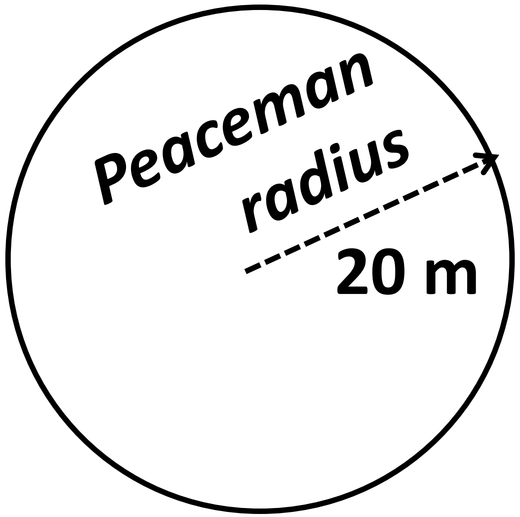
EXPLANATION

Example: 1 GPV *liquid* follows 10-GPV *gas slug*



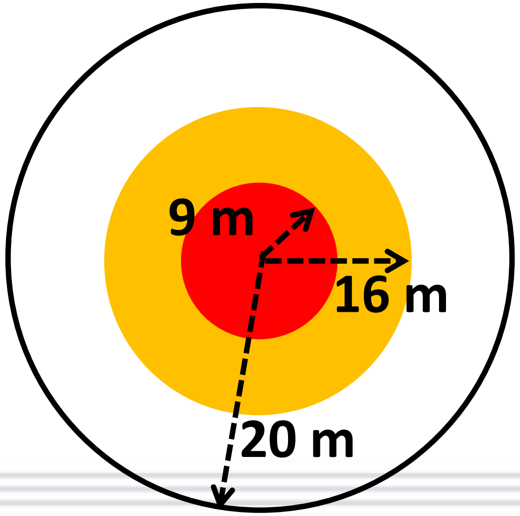
1 Grid block = 100 x 100 m^2

Conventional simulator

Grid-block water saturation: ~0.45

Grid-block mobility: 0.75 md/cP

Dimensionless pressure rise: 300



Bank-propagation model

Collapsed-foam region mobility: 150 md/cP

Gas-dissolution region mobility: 66 md/cP

Liquid-fingering region mobility: 0.85 md/cP

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SUMMARY

- During gas injection following foam
  - ✓ Gas first weakens foam in the entire core.
  - ✓ Then a collapsed-foam region forms near the inlet and propagates slowly downstream.
- During subsequent liquid injection
  - ✓ Liquid sweeps the entire core cross section in the collapsed-foam region.
  - ✓ Liquid fingers through the weakened-foam region.
  - ✓ Gas dissolution is the key for forming the liquid finger and directing liquid to flow through the finger

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SUMMARY

- Conventional simulation using Peaceman model
    - Underestimates injectivity.
    - Propagation of the collapsed-foam region.
    - Cannot represent the effect of previous gas injection on subsequent liquid injectivity
- A new set of experiments would need to be conducted and a new set of parameters fit to those results is necessary for each field application.
- With assumptions and approximations, this model is not predictive. It indicates trends in expected behavior. Be prepared for adjusting injection rate in field.

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SUMMARY

- Simulators face two challenges:
  - Grid resolution near well
  - Mechanisms not represented in model
    - ✓ Evaporation of liquid during gas injection
    - ✓ Dissolution of trapped gas during liquid injection
    - ✓ Capillary-pressure gradients during drying near well
    - ✓ Fingering of liquid through trapped gas

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SUMMARY

- CO_2 instead of N_2?
  - We expect similar overall behavior incl. bank-propagation
  - Liquid evaporation and foam collapse during gas injection could be different
  - CO_2 is more soluble
    - ✓ Faster gas dissolution into water
    - ✓ Faster propagation of the gas-dissolution front during liquid injection

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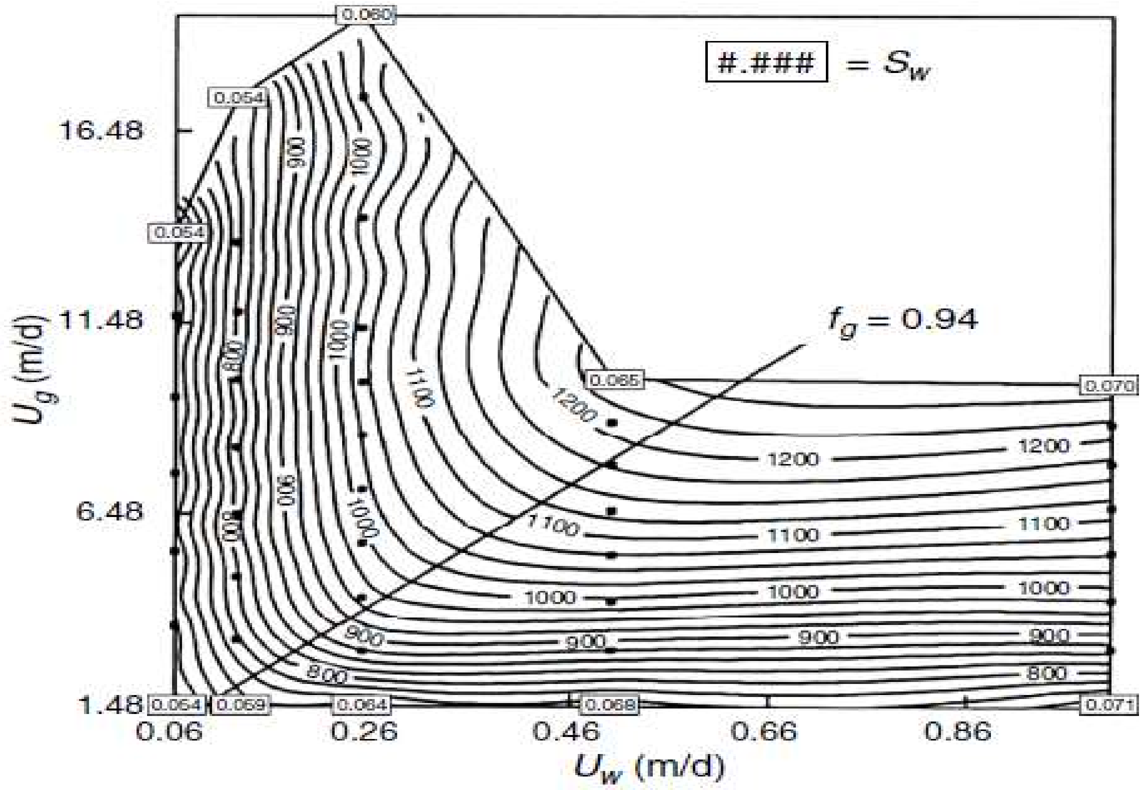
OUTLINE

- Foam for gas-mobility control
- Experiment investigation of foam flow regimes with oil
- Modeling of steady-state foam-oil flow
- CT study of foam corefloods with oil
- Summary
- Current challenges

FOAM FLOW REGIMES

- Foam-flow regimes in porous media
- High-quality regime at the upper left
- Low-quality regime at the lower right
- Crucial starting point for deeper exploration in geological formations



Pressure gradient as a function of U_w and U_g, Osterloh and Jante (1992)

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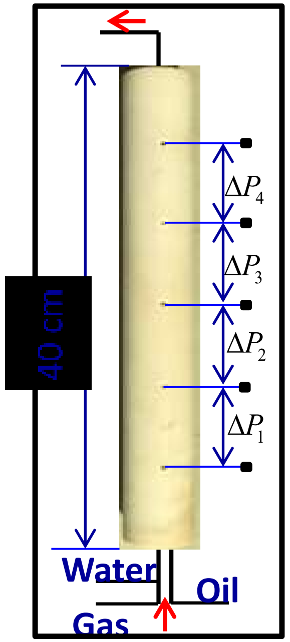
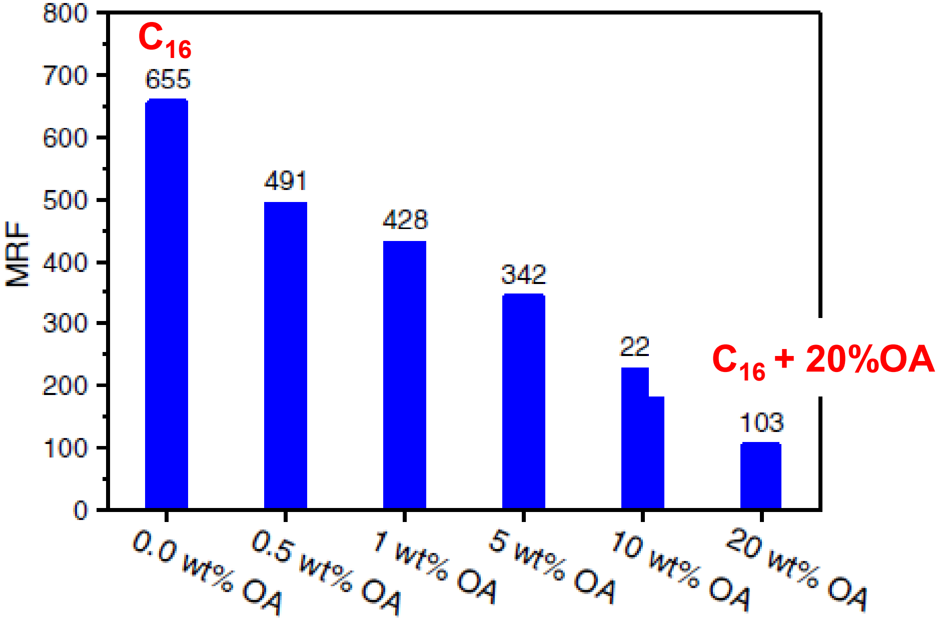
EXPERIMENTAL INVESTIGATION: FOAM-FLOW REGIMES WITH OIL

- Co-inject foam and oil to ensure steady state
- Fix U_o/U_w ratio to quantify the effect of oil



Bentheimer core sample



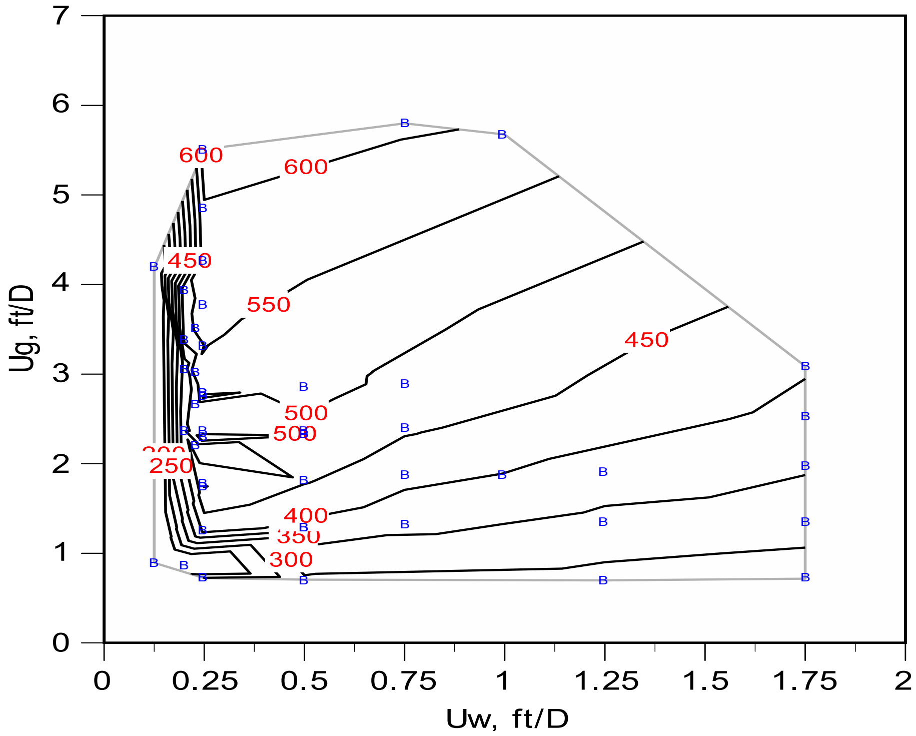
Foam mobility-reduction factor with oil

- Two types of model oils used:
- Hexadecane (C16), benign to foam stability
- Mixture of C16 and oleic acid (OA), very harmful to foam

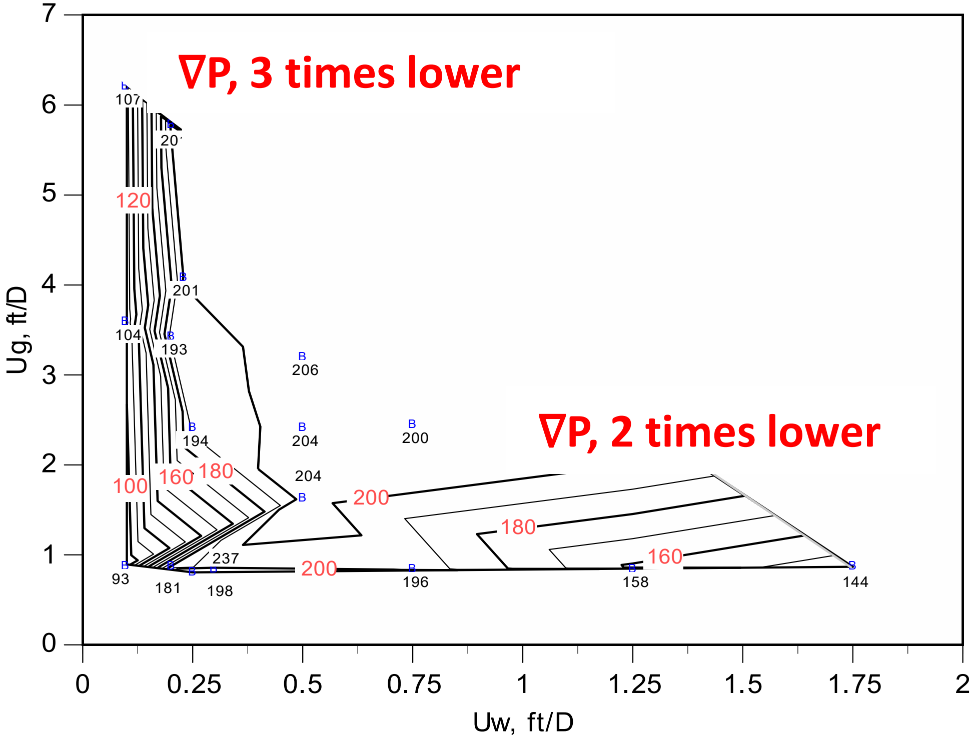
EXPERIMENTAL INVESTIGATION: FOAM AND C_{16}

- Two regimes still exist, oil affects both regimes, high-quality regime is more vulnerable to oil
- Low-quality, tilted upward, not independent of U_w.

Reference without oil



U_o/U_w=0.25 with C_{16}



∇P, 3 times lower

∇P, 2 times lower

Tang, J. et. al., SPE J., 2019

Steady-state foam flow without oil

Steady-state foam flow with C_{16}

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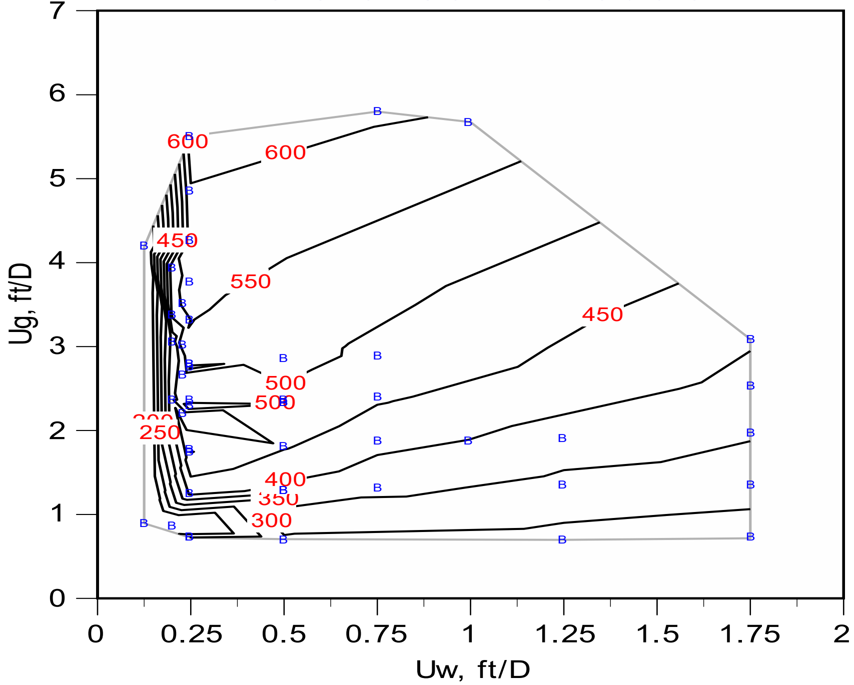
EXPERIMENTAL INVESTIGATION: FOAM AND C_{16} + 20%OA

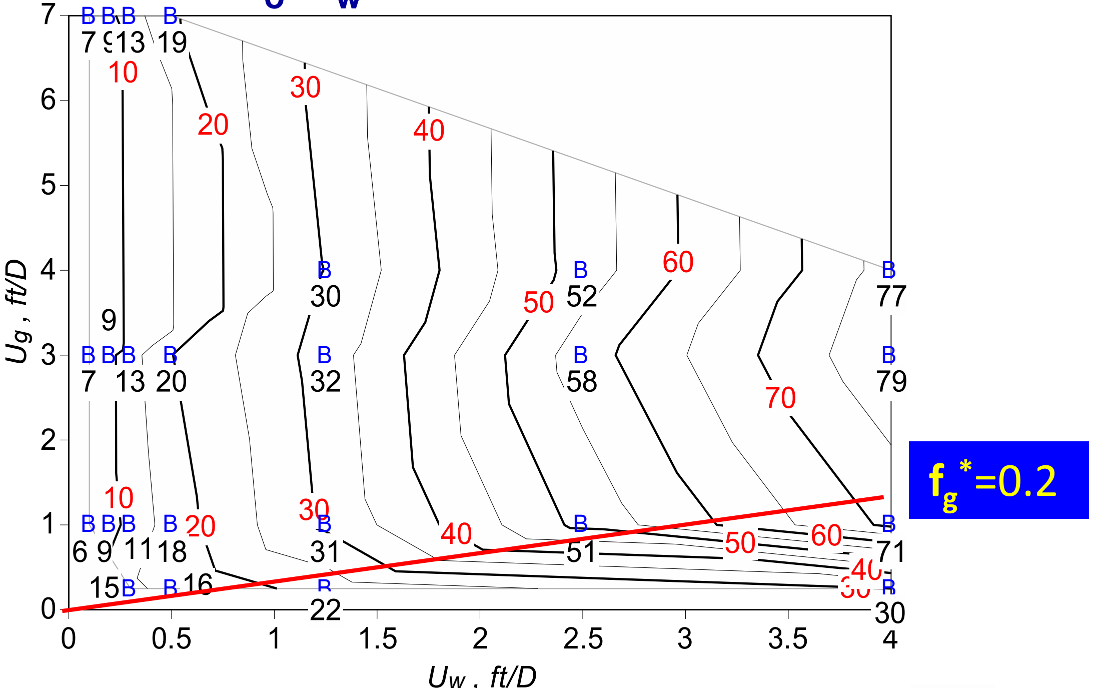
- Oil type plays as significant a role as oil saturation
- Gas-mobility reduction is 40x lower in the high-quality regime and 7x lower in the low-quality regime

Reference without oil



Steady-state foam flow without oil

U_o/U_w=0.25 with 20%OA



Steady state foam flow with 20% OA in oil

Tang, J. et. al., SPE J., 2019

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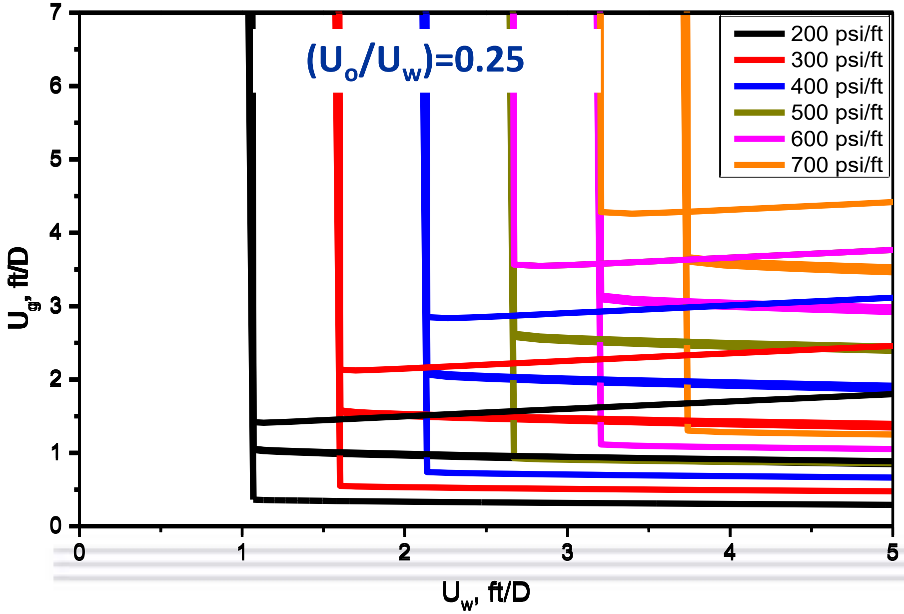
MODELLING OF STEADY-STATE FOAM + OIL FLOW

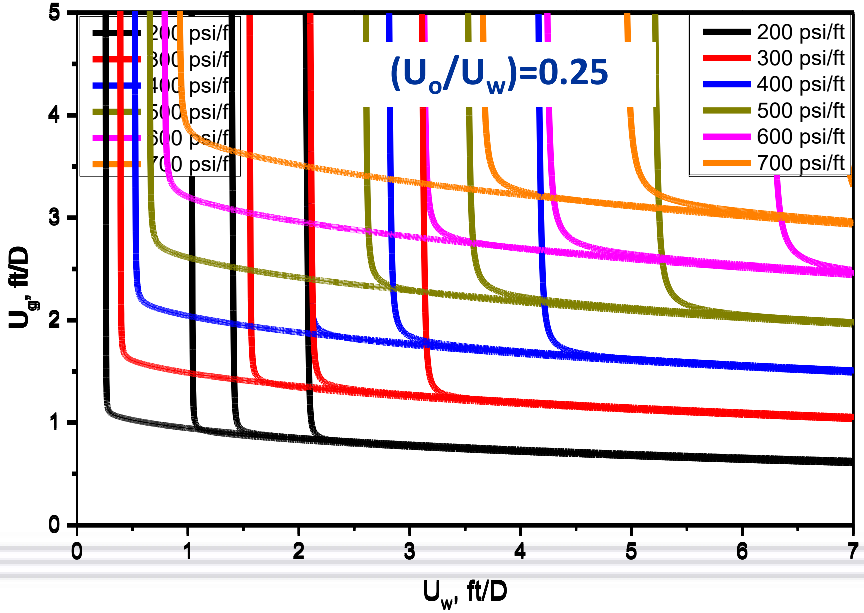
- Implicit-texture modelling: "wet-foam" algorithm and "dry-out“ algorithm
- Contour shift reflects the effect of oil on each regime.
- Each algorithm represents the effect of oil only on one regime or the other.

$$k_{rg}^{\ f} = k_{rg}^{\ o} \times FM(S_w, S_o)$$

With wet-foam algorithm



With dry-out algorithm



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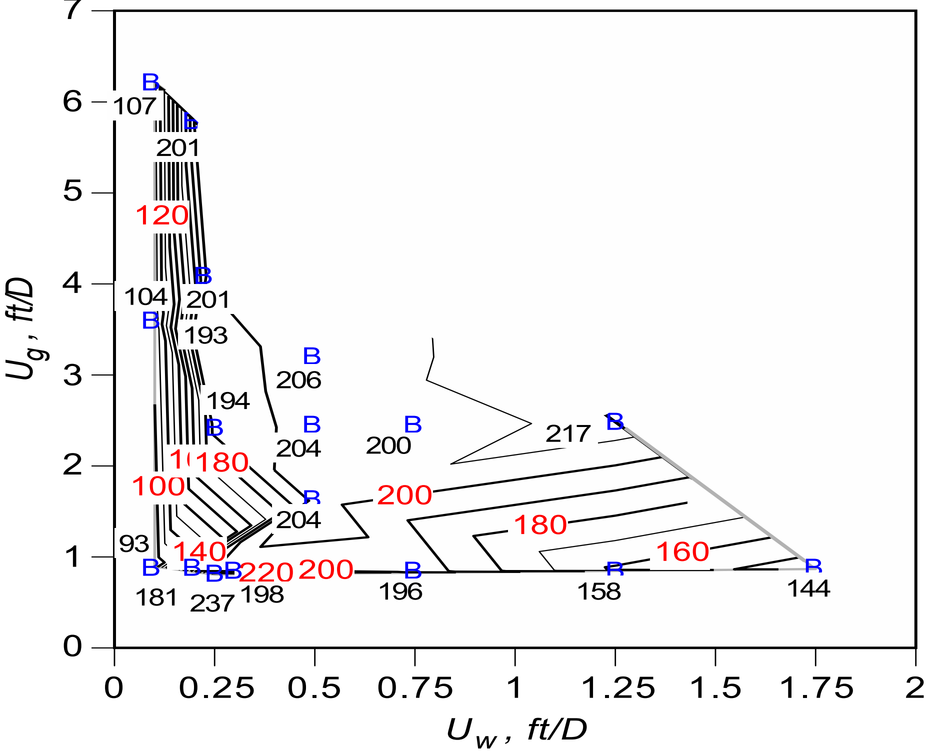
MODELLING OF STEADY-STATE FOAM + OIL FLOW

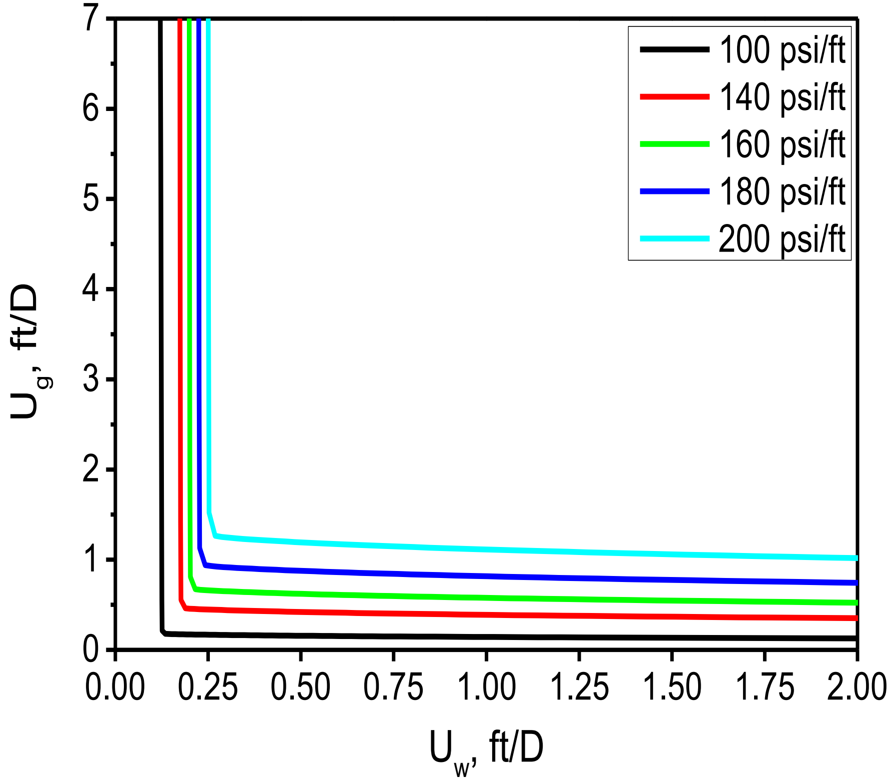
MODEL FIT TO STEADY-STATE FOAM WITH C16

- Foam properties were estimated from steady-state data.
- Good match to experimental data, except for the upward-tilting ∇P contours in the low-quality regime.

Data on foam flow with C_{16}



Model fit to data



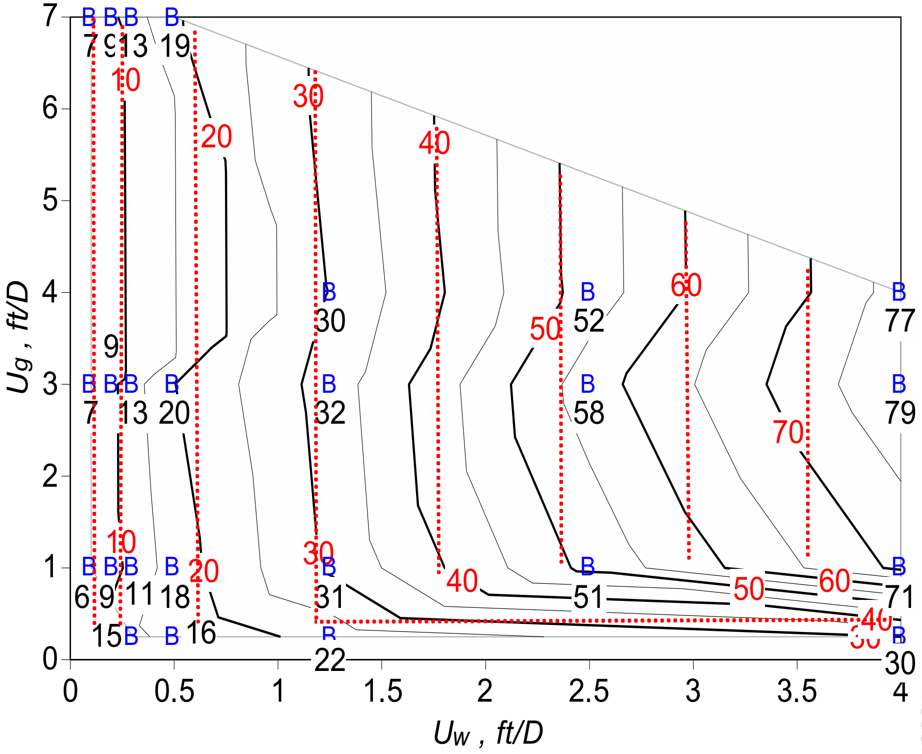
Tang, J. et. al.,
SPE J., 2019

MODELLING OF STEADY-STATE FOAM + OIL FLOW

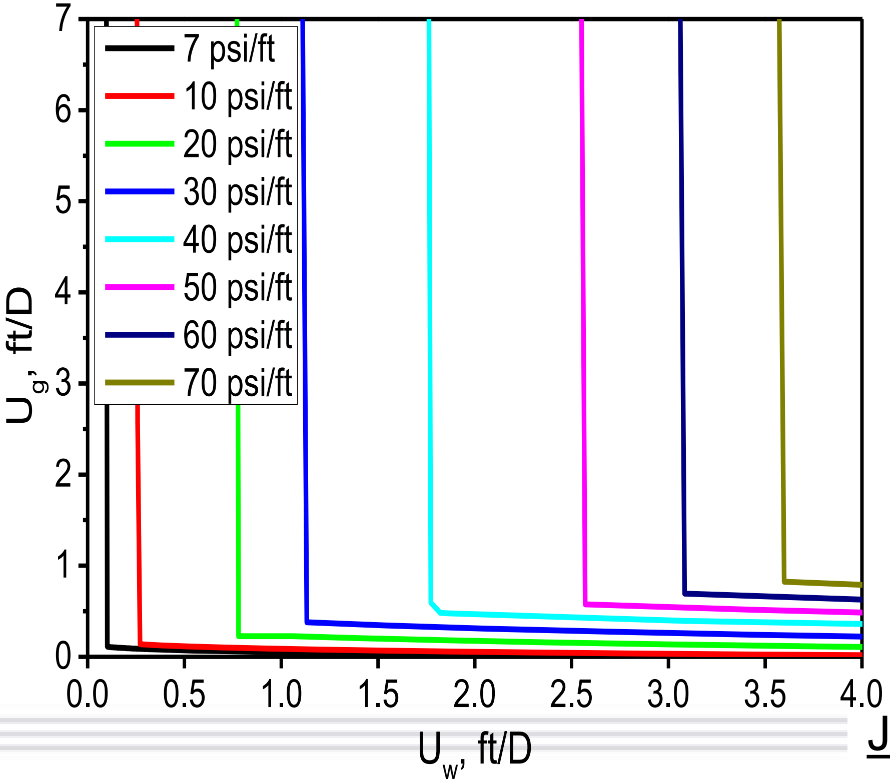
MODEL FIT TO STEADY-STATE FOAM WITH C16 + 20% OA

- One must combine wet-foam and dry-out algorithms to represent the effect of oil on both regimes.

Data on foam flow with 20% OA



Model fit to data



Tang, J. et. al., SPE J., 2019

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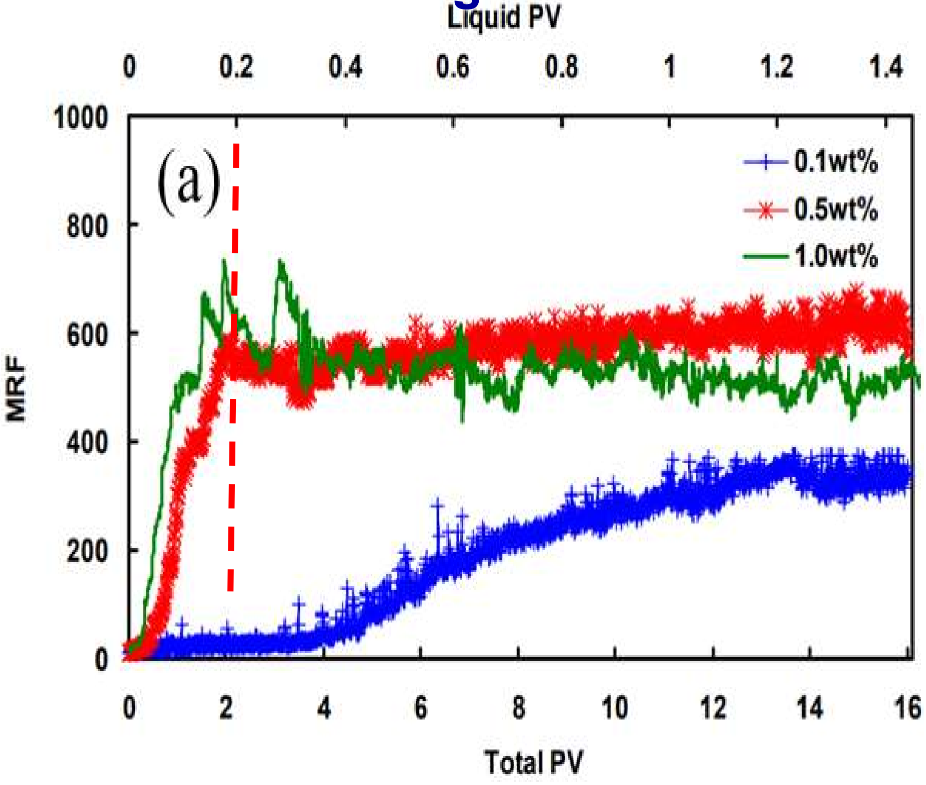
CT STUDY OF DYNAMIC FOAM COREFLOODS WITH OIL

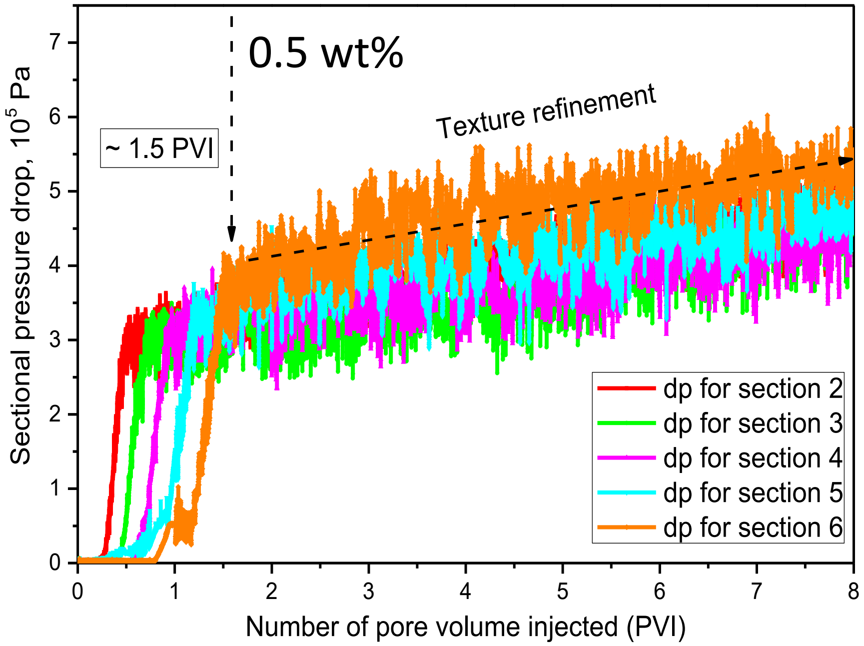
- Pre-generated foam vs. in-situ-generated foam **with C16.**
- Two injection methods show similarities in foam dynamics.
- Foam develops quickly, followed by refinement in texture.

In-situ-generated foam



Mobility reduction factor (MRF)
Simjoo and Zitha (2013)

Pre-generated foam



Sectional pressure drop
Tang (2019)

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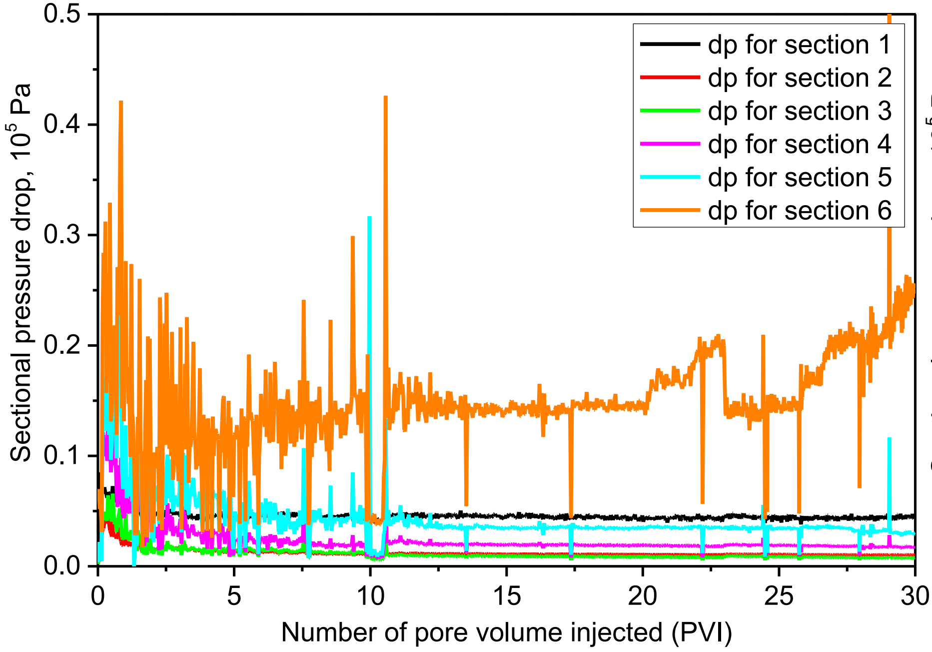
CT STUDY OF DYNAMIC FOAM COREFLOODS WITH OIL

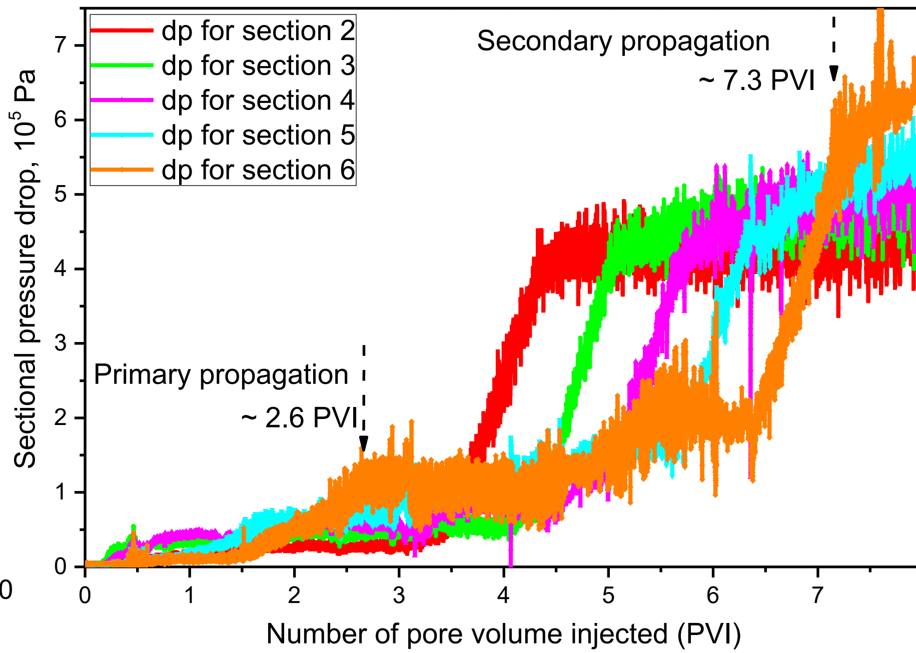
- Pre-generated foam vs. in-situ-generated foam **with C16 + 20% OA.**
- Foam behavior is very different.
- In-situ foam generation is very difficult even at **S_{or} ~0.1**.
- Pre-generated foam shows two stages of propagation.

In-situ-generated foam



Sectional pressure drop

Pre-generated foam



Sectional pressure drop

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SUMMARY

❑ Foam-flow regimes in porous media with oil

- The two regimes for foam without oil apply to foam with oil.
- Oil affects both regimes, but has a stronger impact on the high-quality regime.

❑ Modeling of foam flow with oil

- Each of the two algorithms for foam represents the effect of oil only on one regime or the other.
- The currently applied foam model, though simplified, give a good match to data.

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SUMMARY

☐ Dynamics of foam with oil

  - Pre-generated foam behaves very differently than in-situ generated foam, depending on oil type.
  - Currently applied foam models needs further investigation for reliable prediction of foam EOR.

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CURRENT CHALLENGES

- ☐ Need an effective approach for estimation of oil-related foam-simulation-model parameters.
- ☐ Implicit-texture modeling of foam EOR uses steady-state data to predict dynamic behavior. The reliability needs to be verified.
- ☐ With N_2 foam, oil affects foam through its interaction with aqueous phase. With CO_2 foam, oil interacts with both aqueous and gas phases, especially when miscibility is involved.

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Studies of Foam for EOR and CO_2 storage: Liquid Injectivity[3], the Effect of Oil on Foam[2], and Generation In-situ in Heterogeneous Formations[1]

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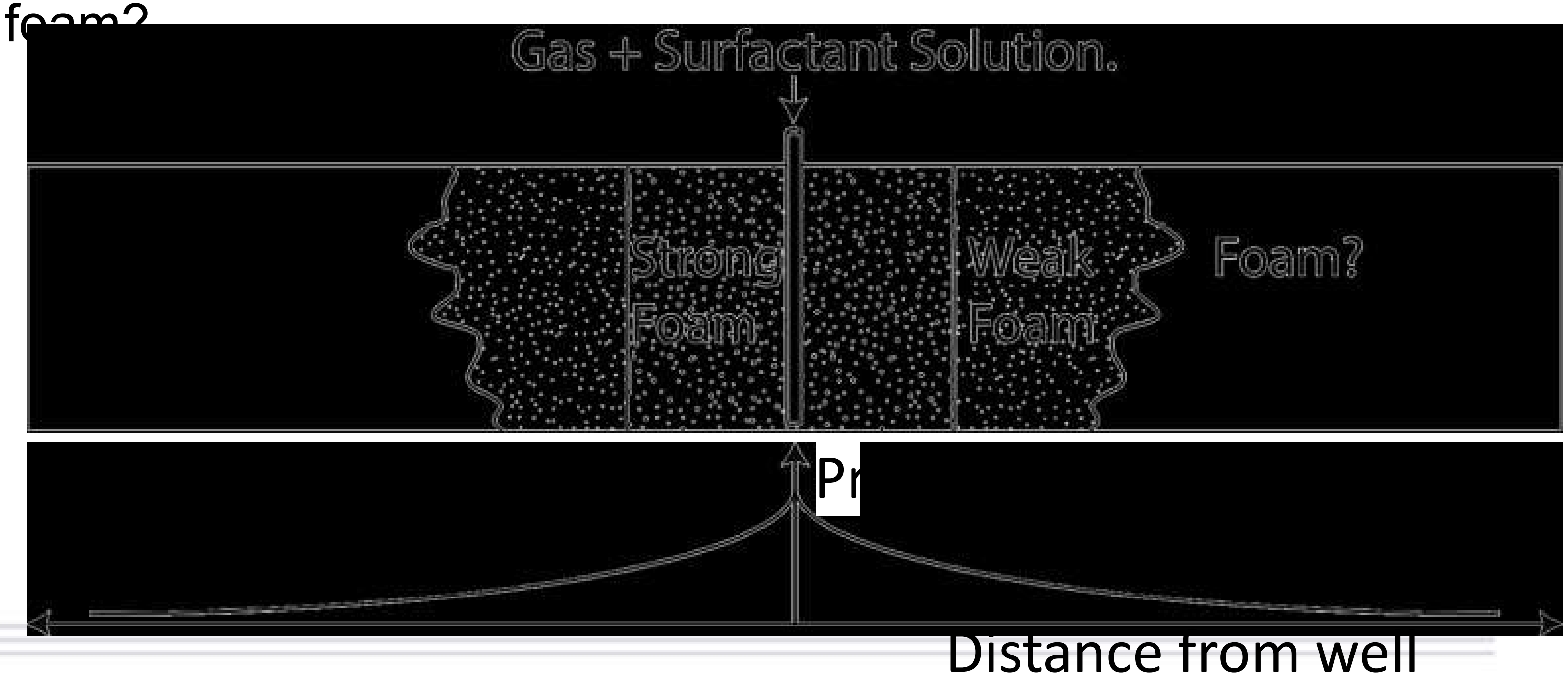
Foam Generation by Snap-off in Flow Across a Sharp Permeability Transition

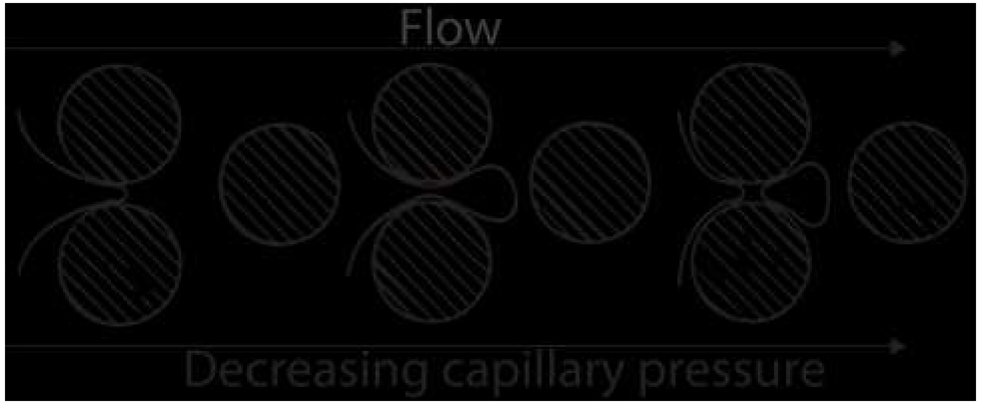
HOW DOES FOAM GENERATE IN POROUS MEDIA?

- What dominates in the reservoir?
  - In the near-well region,
    - SAG flood, gas draining liquid → leave-behind, snap-off
    - High ∇P → lamella division
  - What happens away from the wells?
    - Low ∇P, low velocity, surfactant and gas slugs might've mixed.
    - Can we still expect fo



WHY ARE WE INTERESTED IN THIS?

- Snap-off doesn’t only happen during drainage.
- There are several documented ways in which snap-off can occur.[1]
- A particular mechanism of snap-off could help generate foam and improve sweep efficiency away from wells.



Snap-off (Roof, 1970)

❶ ------------------------- -------------------------

❷ ------------------------- -------------------------

❸ ------------------------- -------------------------

❹ ------------------------- -------------------------

❺ Snap-off in flow across a sharp increase in permeability.

❻ ------------------------- -------------------------

❼ ------------------------- -------------------------

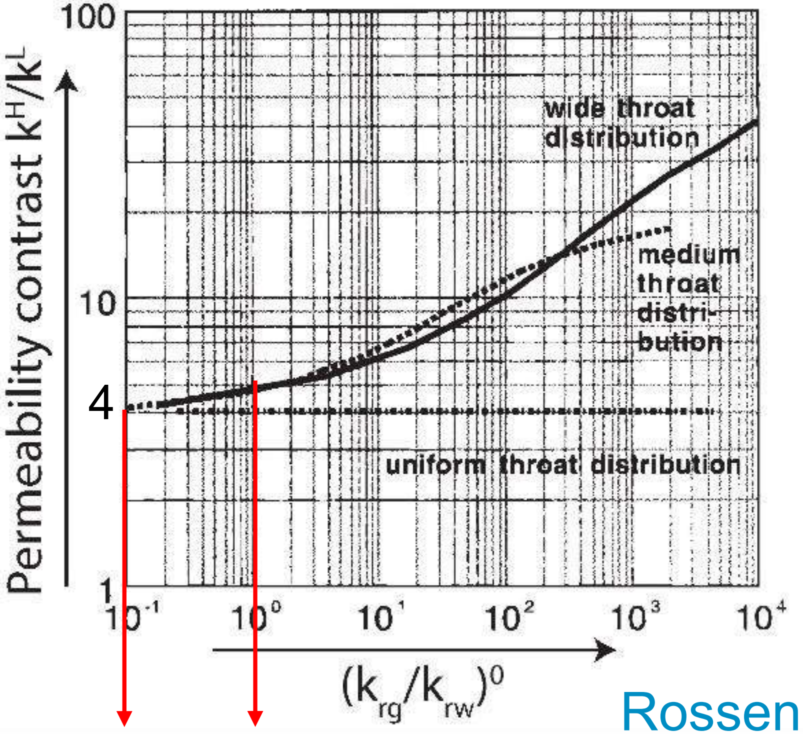
---

[1] Rossen, W.R., 2003

WHY ARE WE INTERESTED IN THIS?

- Snap-off can cause foam generation independent of pressure gradient in flow across a sharp increase in permeability (Falls, A.H. et al. 1988, Hirasaki. et al. 1997).

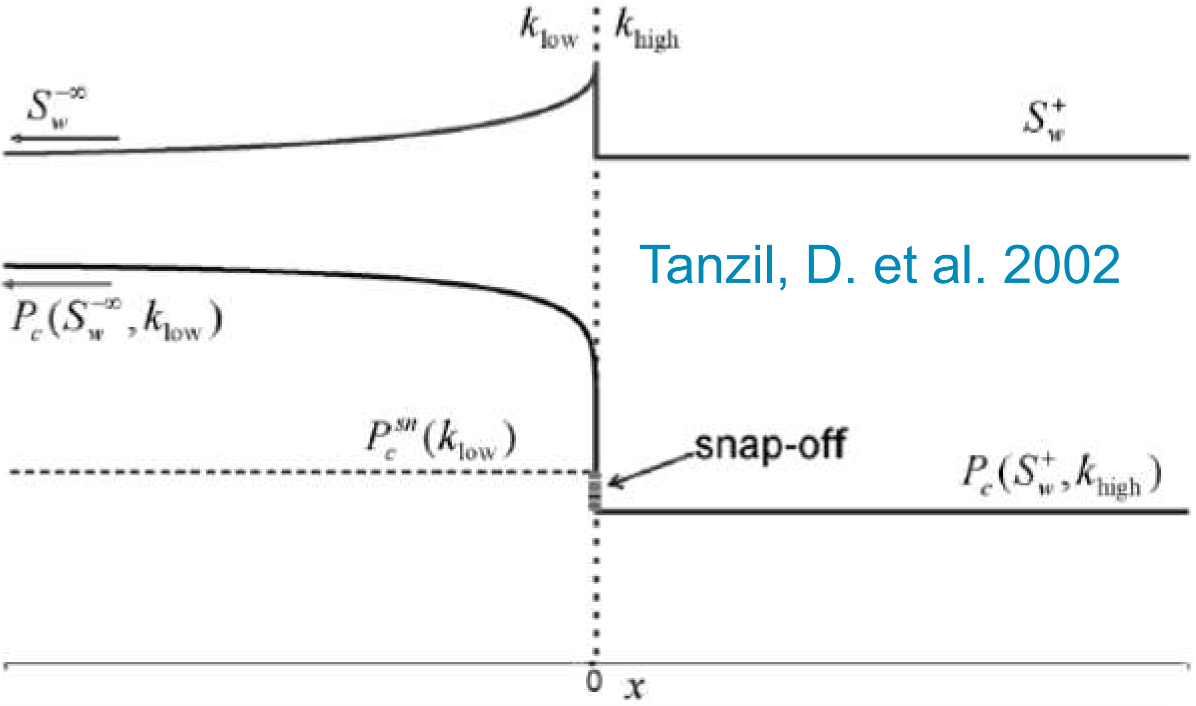
- Previous experiments were all under drainage and questions still remain.



f_g=80% f_g=90%

Rossen, W.R., 1999

“Internal” capillary end-effect



Tanzil, D. et al. 2002

WHY ARE WE INTERESTED IN THIS?

- ☐ Sharp heterogeneities do exist in subsurface formations[1,2,3] (e.g. laminations, cross-strata, layer boundaries).

- ☐ Design an experiment with no foam generation by other mechanisms.

- ☐ Do we observe foam generation? Validate (or contradict) theoretical predictions.

- ☐ Investigate the effect of:
    - permeability contrast (k^H/k^L) – Shah et. al., SPE J., 2018
    - fractional flow (f_g) – Shah et. al., SPE J., 2019
    - velocity (u_t) – Shah et. al., SPE J., 2019

- ☐ Does the foam mobilize and propagate at field-like velocities?

[1] Reineck and Singh, 1980

[2] Collinson and Thompson, 1989

[3] Hartkamp-Bakker, 1993

EXPERIMENTAL METHODOLOGY

Procedure:

CO_2 flush

↓

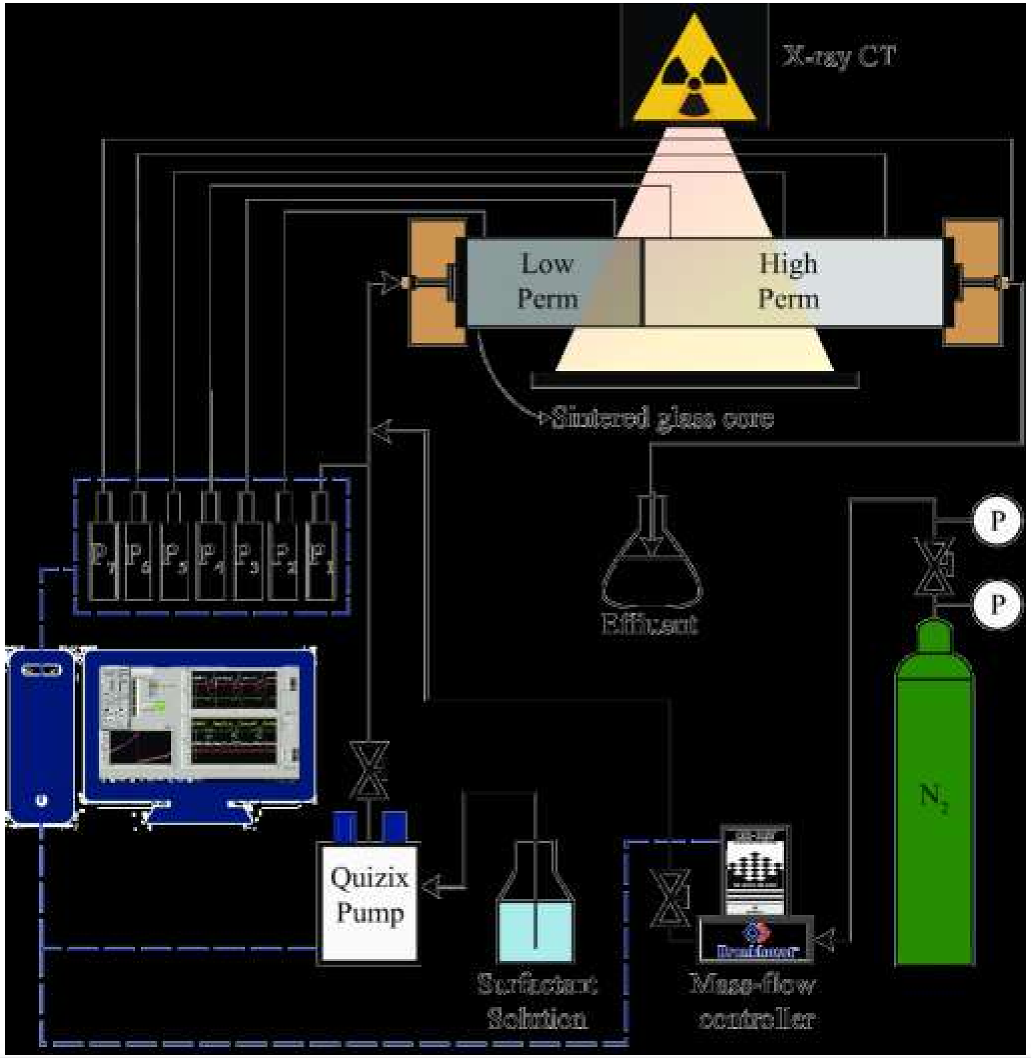
Saturate with brine
(1 wt.% NaCl)

↓

Inject N_2 + brine
(at desired f_g)

↓

Inject N_2 + surfactant
solution
(0.5 wt.% $\gg$ CMC,
1 wt.% NaCl)



RESULTS

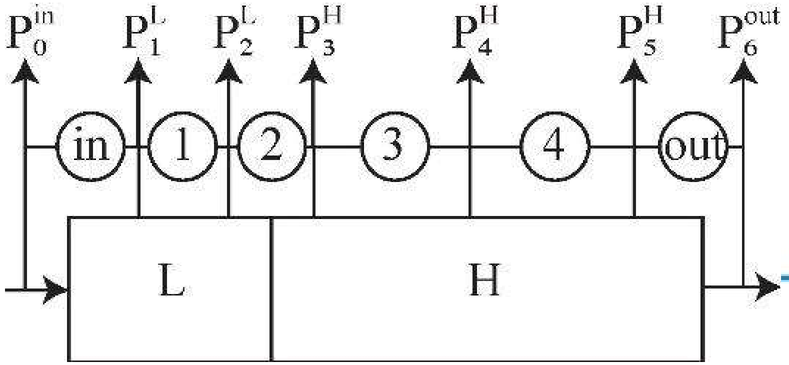
In-situ saturation measurements

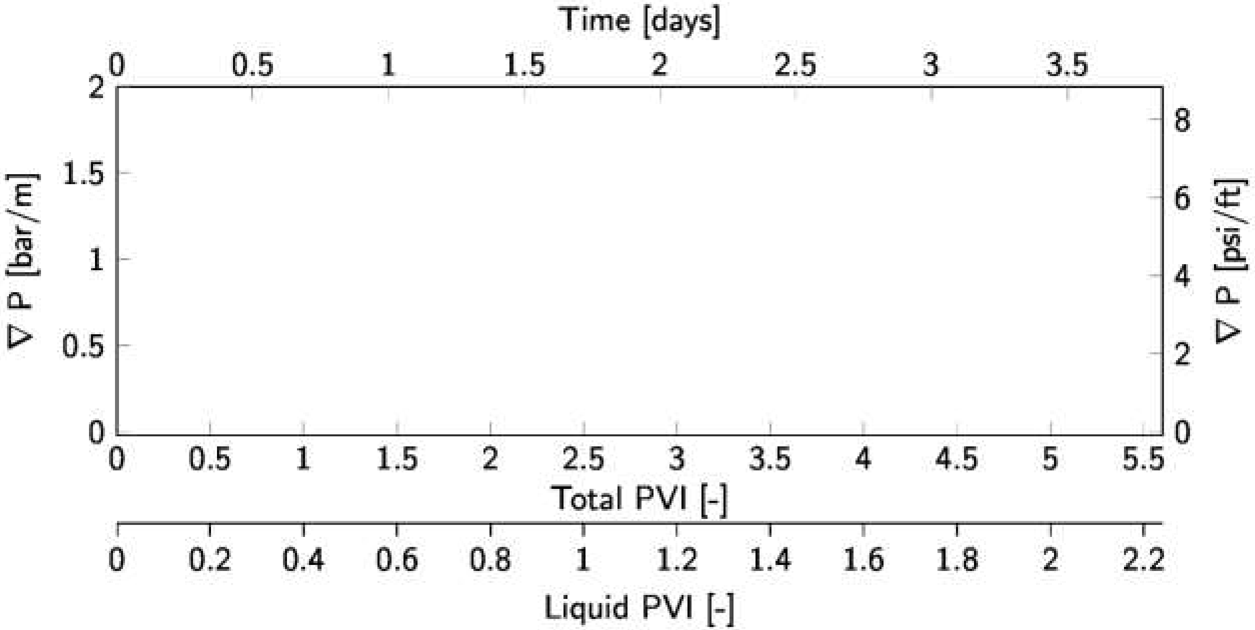
- ❑ So what do we observe?
- ❑ Here’s an experiment assisted with CT-scanning, u_t=0.67 ft/d, f_g=60%, $k^H/k^L \approx 4:1$, core placed horizontally.

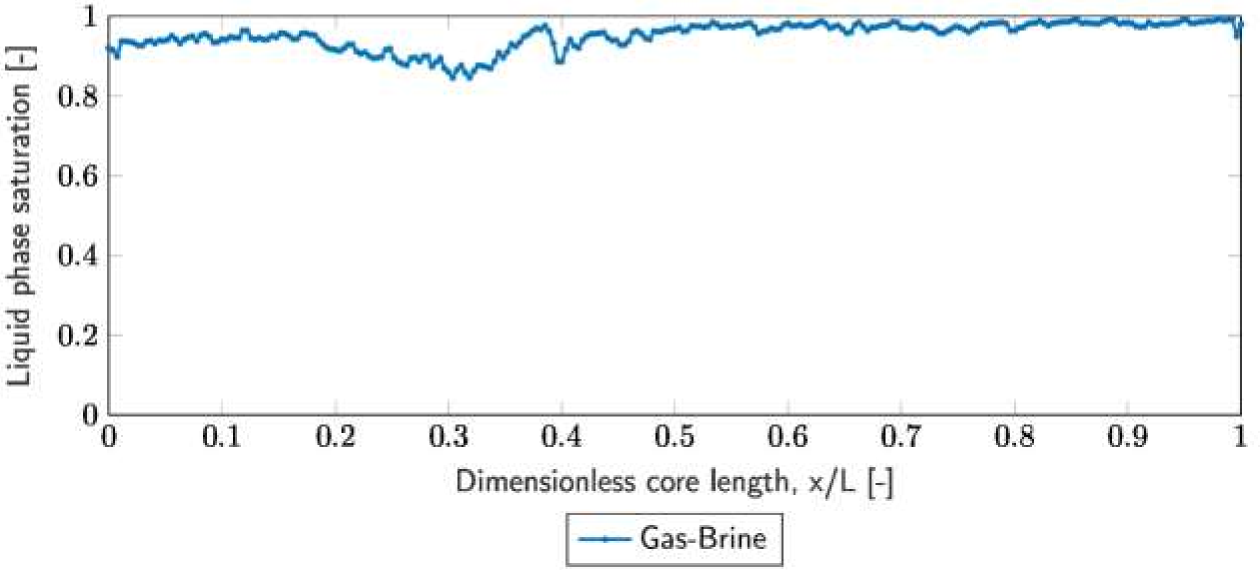
Shah, S.Y. et. al., SPE J., 2019

RESULTS

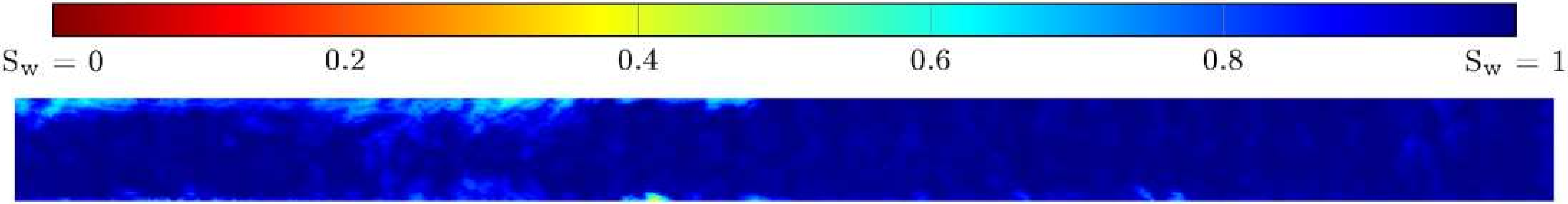
In-situ saturation measurements





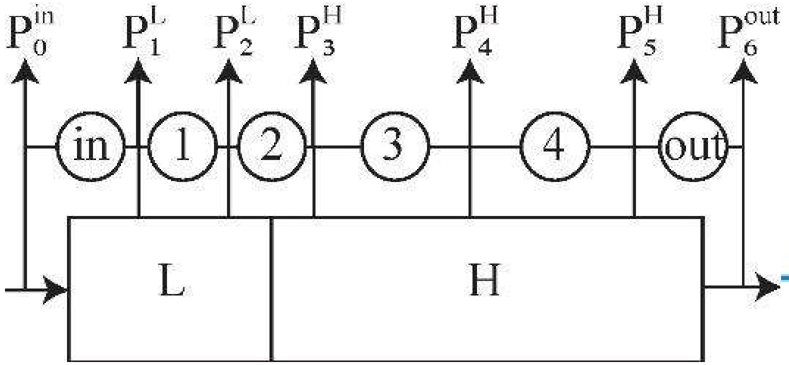


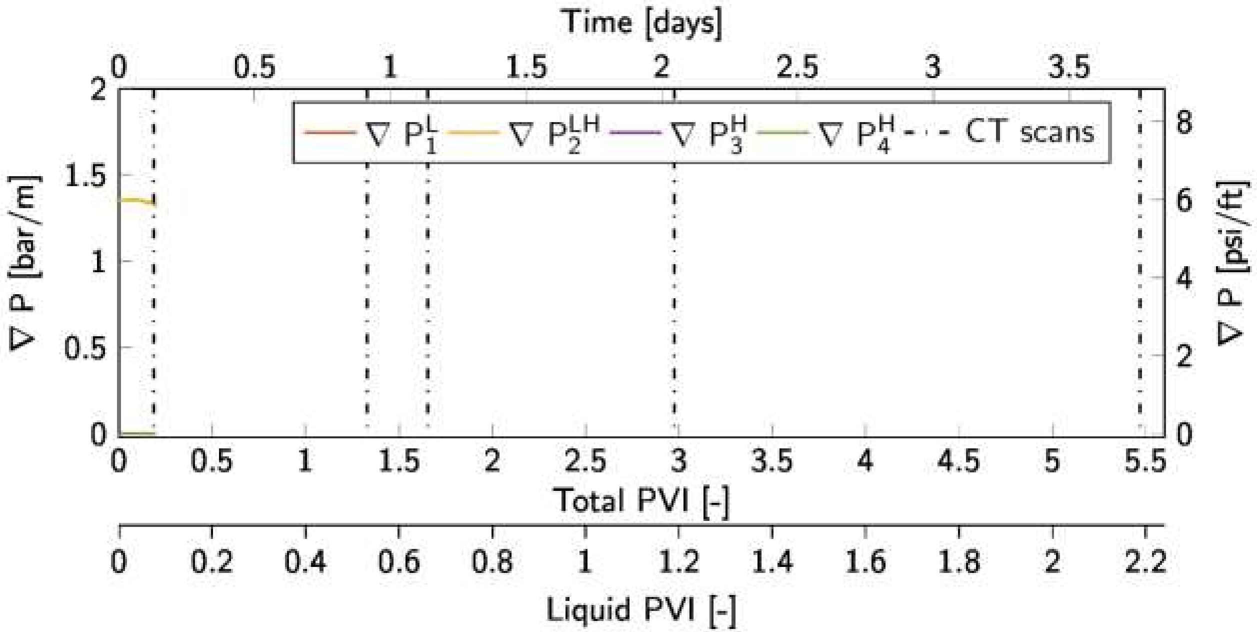
Gas-Brine steady-state

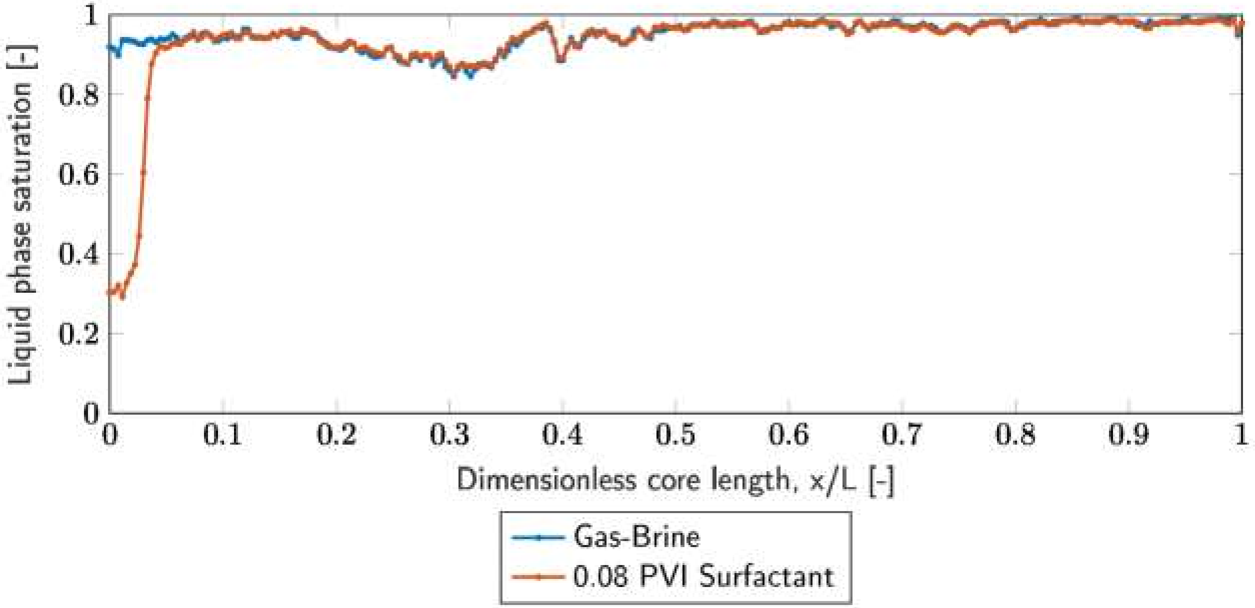


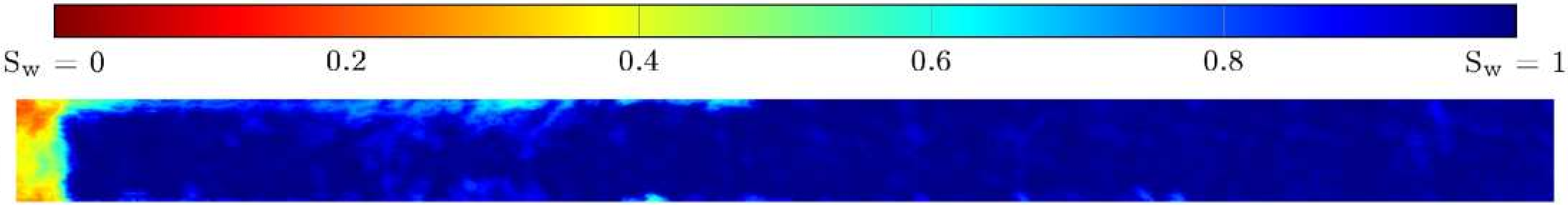
RESULTS

In-situ saturation measurements





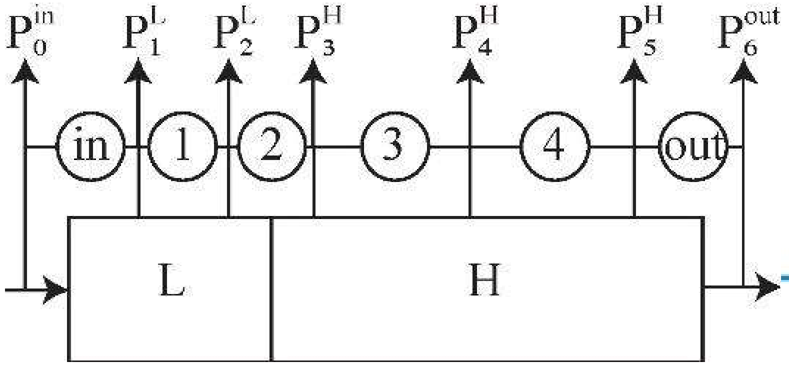


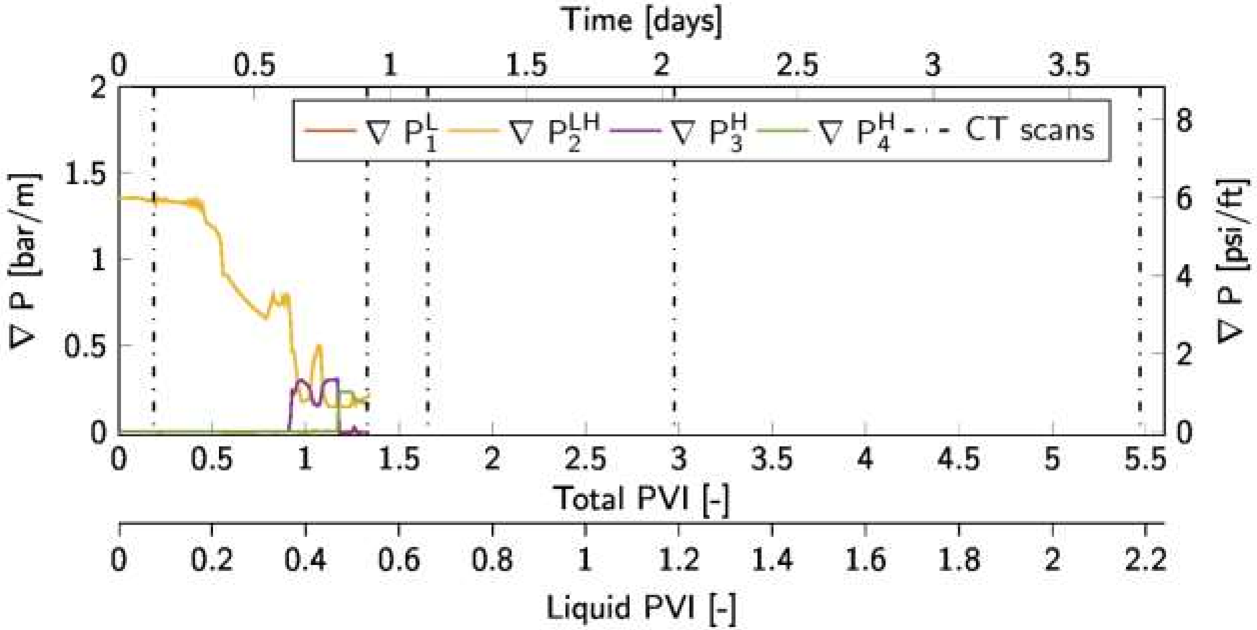


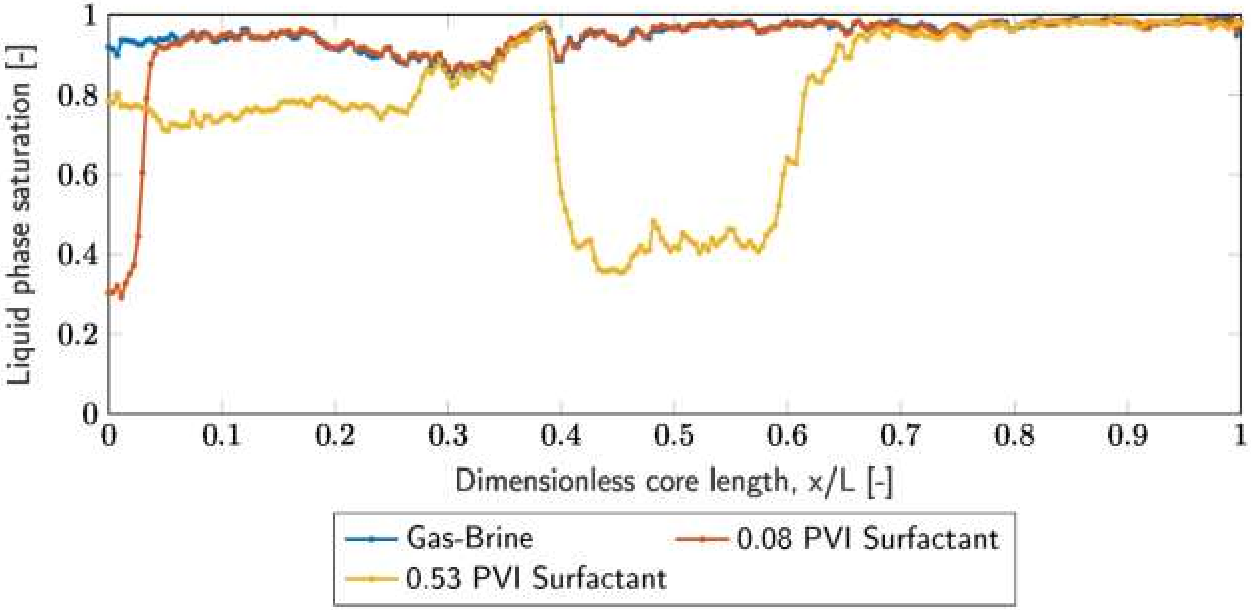
Gas-Surfactant
0.08 PVI Liquid

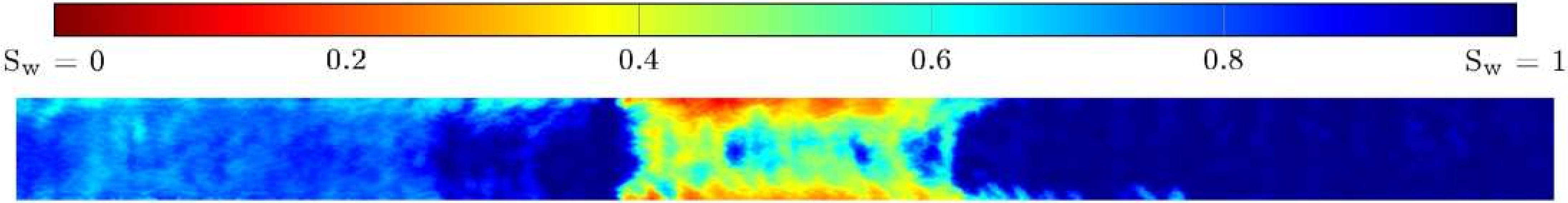
RESULTS

In-situ saturation measurements





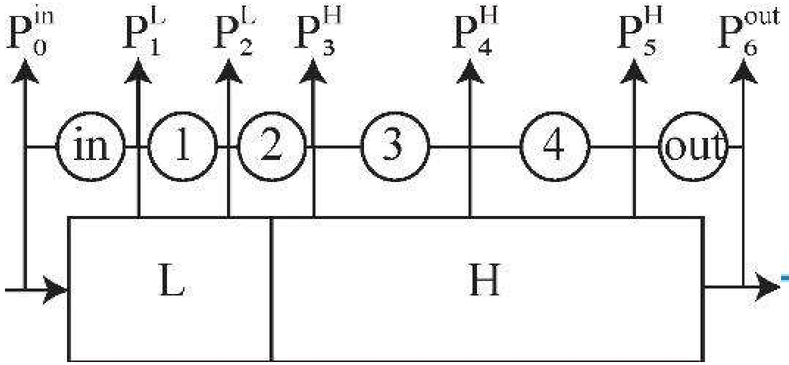


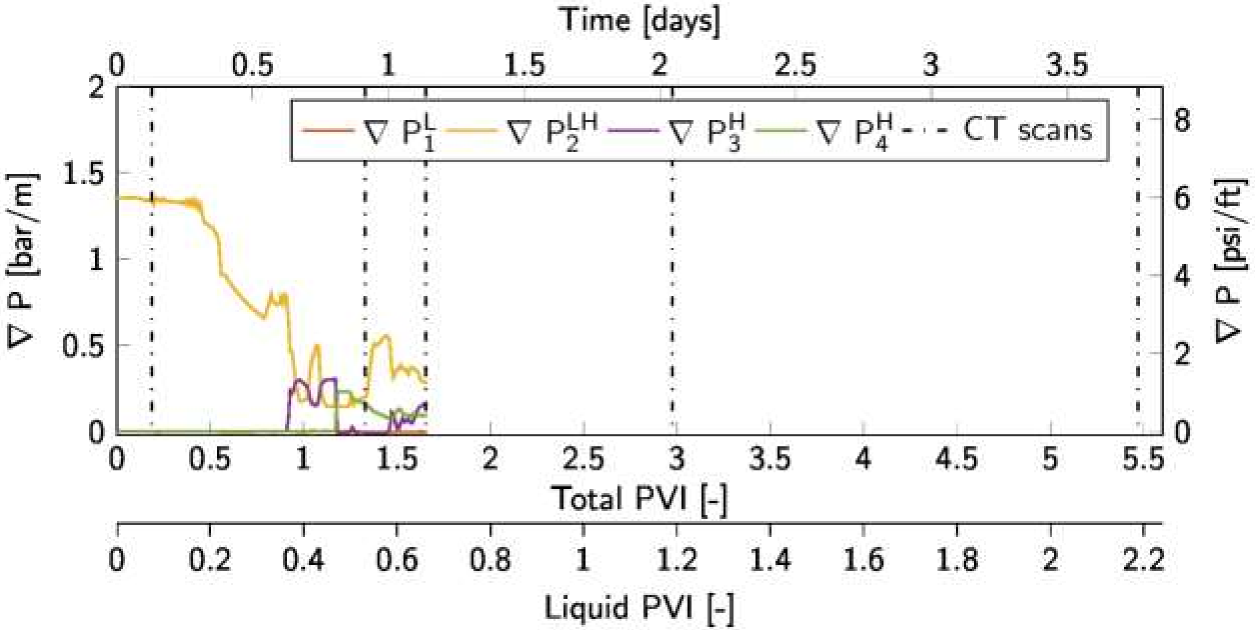


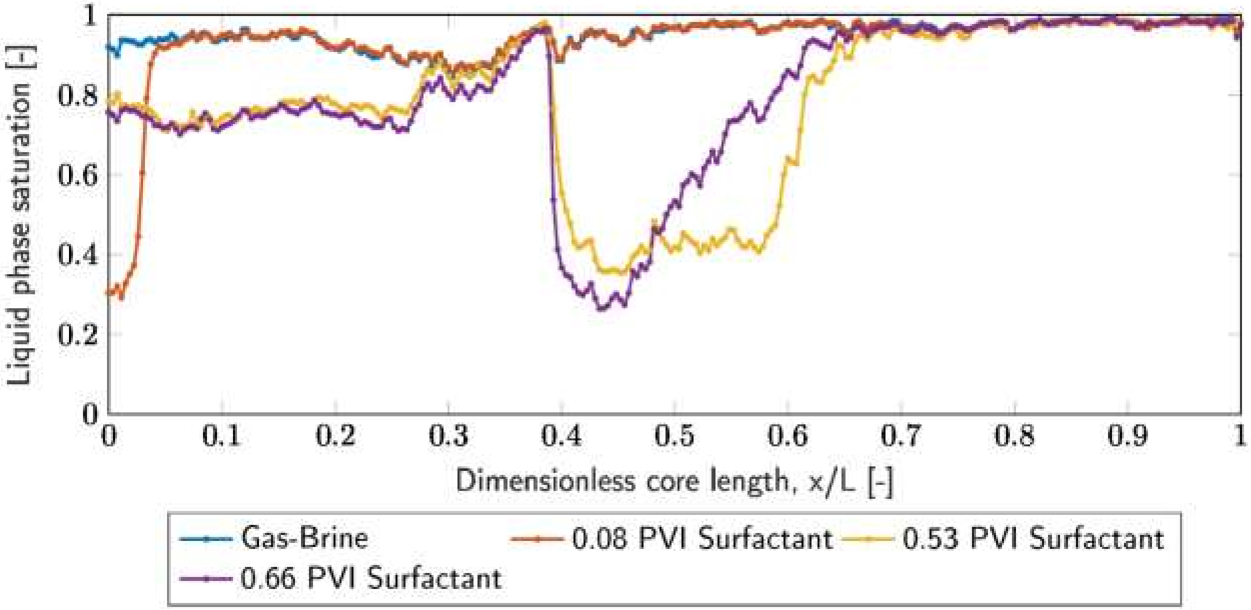
0.5 PVI Liquid

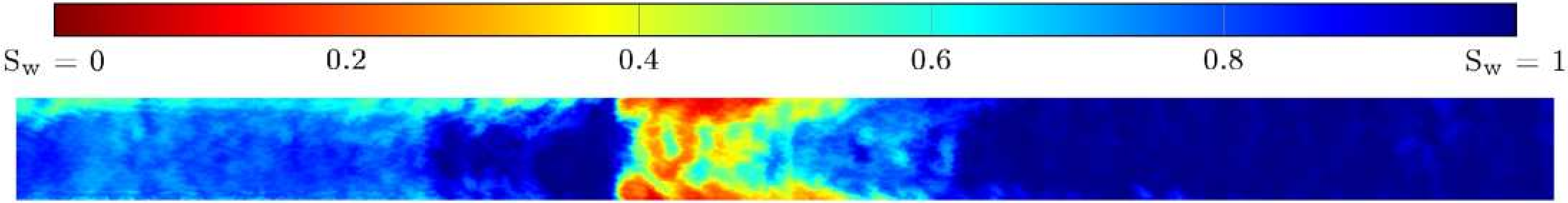
RESULTS

In-situ saturation measurements





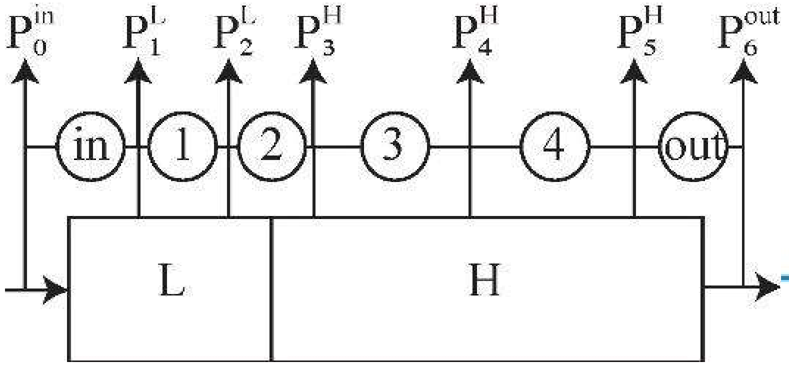


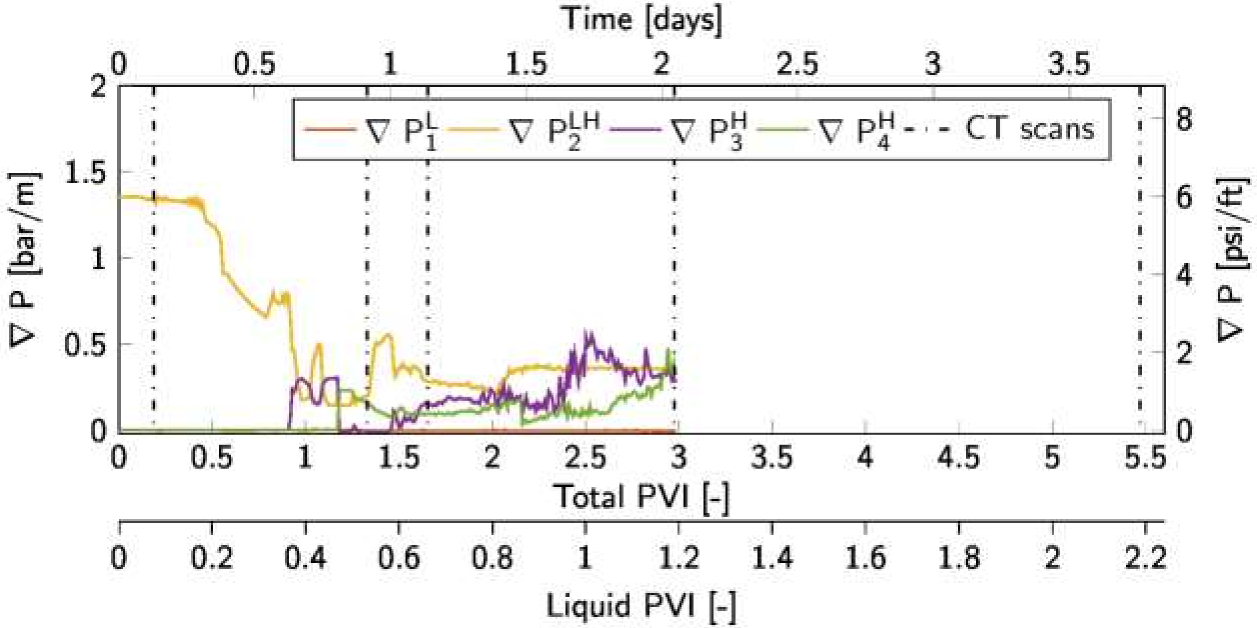


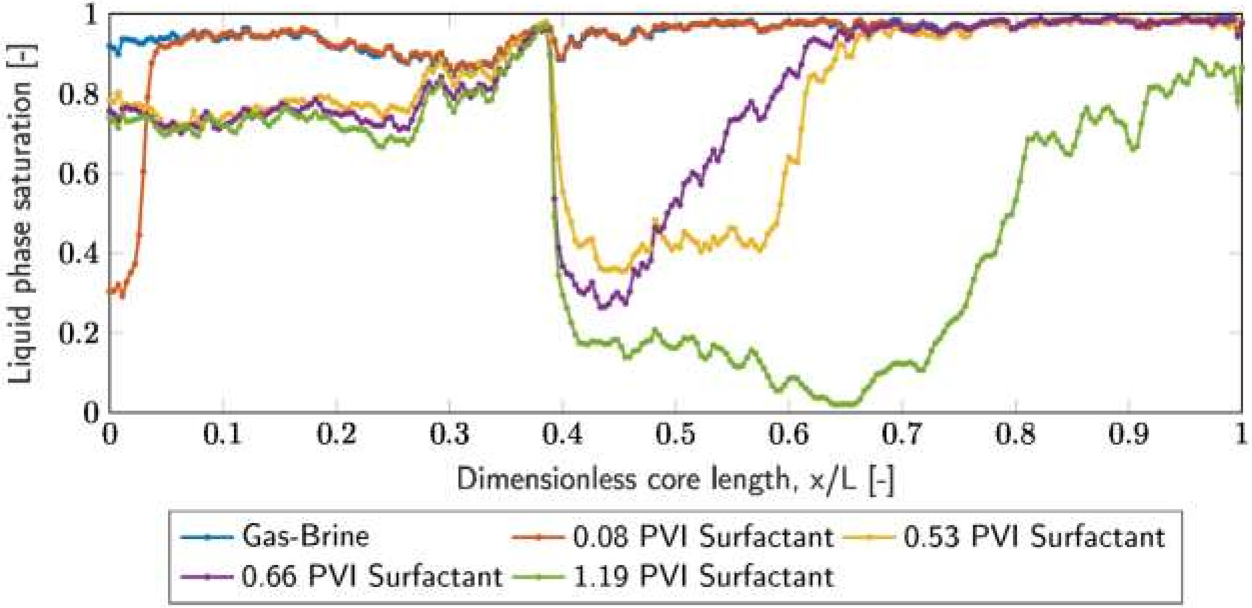
0.7 PVI Liquid

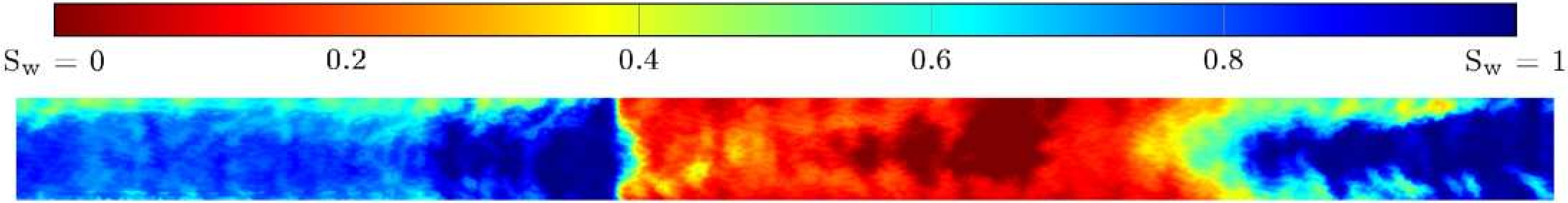
RESULTS

In-situ saturation measurements





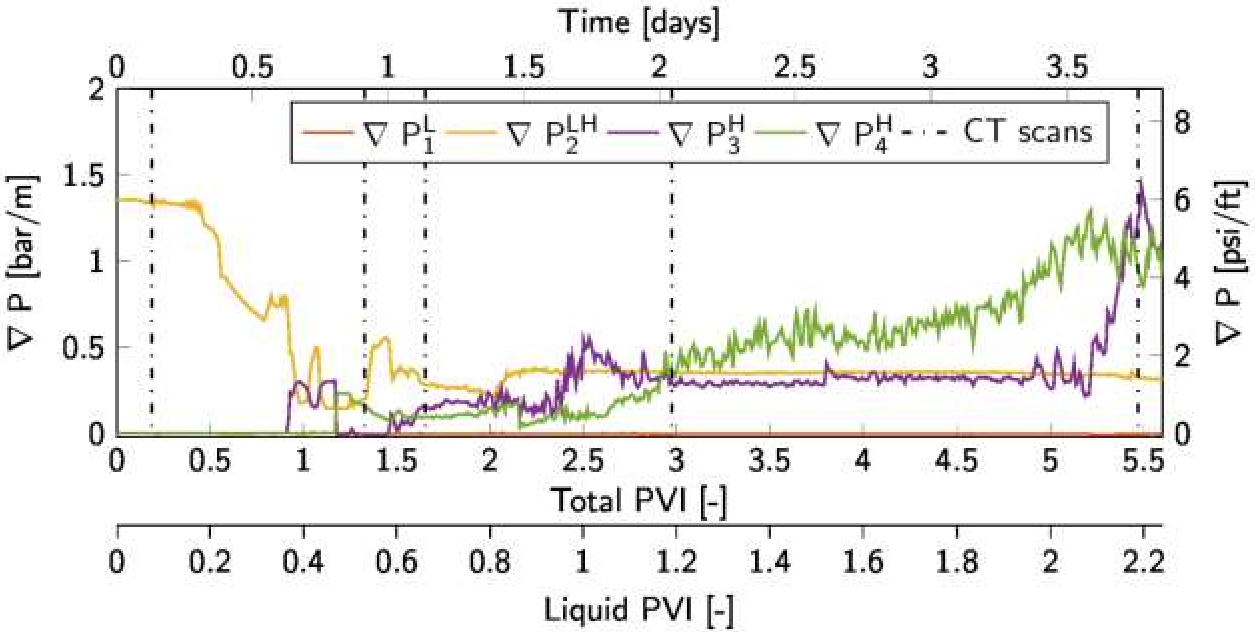


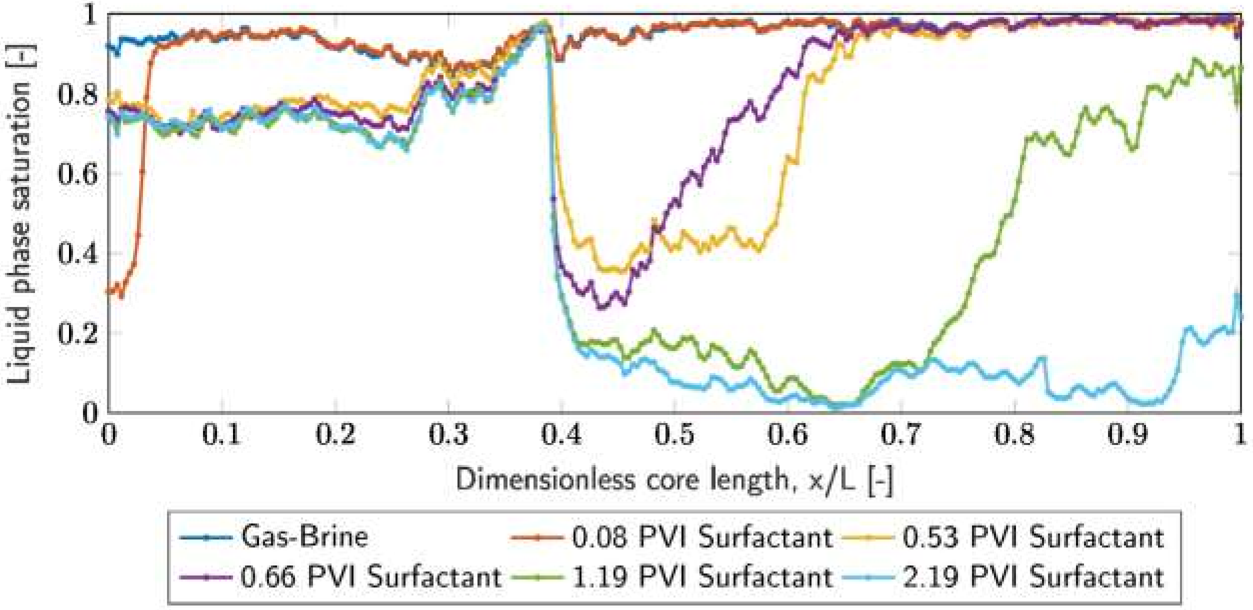


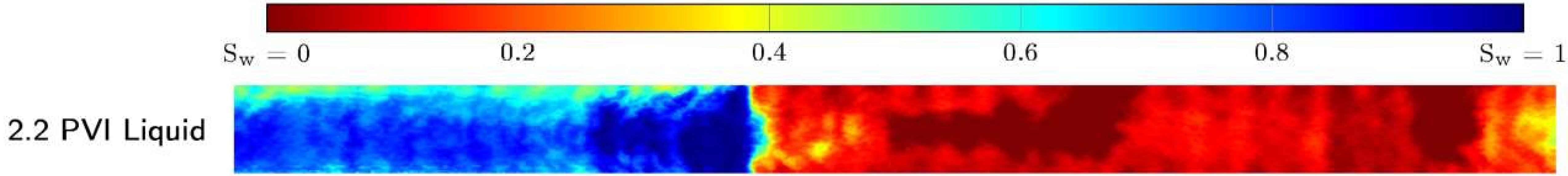
1.2 PVI Liquid

RESULTS

In-situ saturation measurements



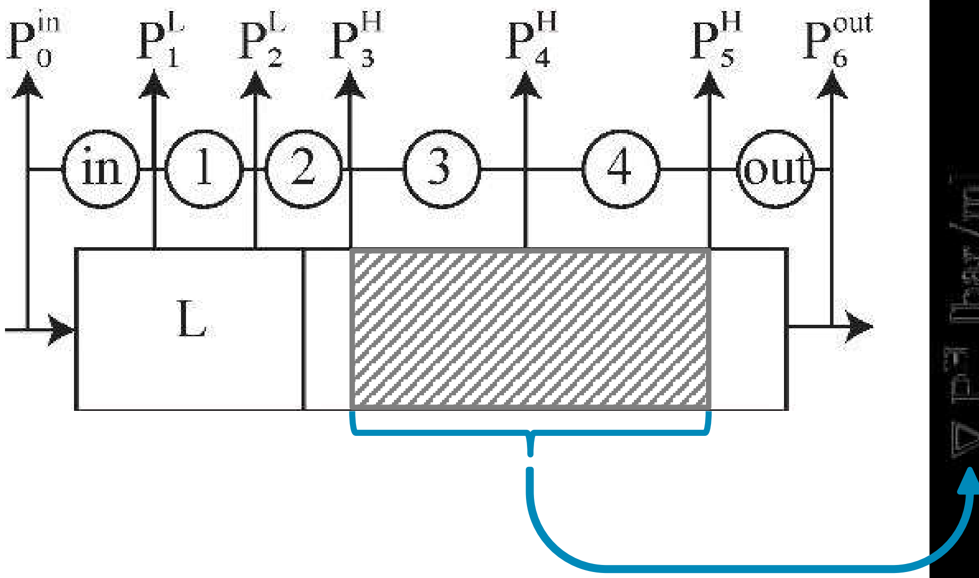


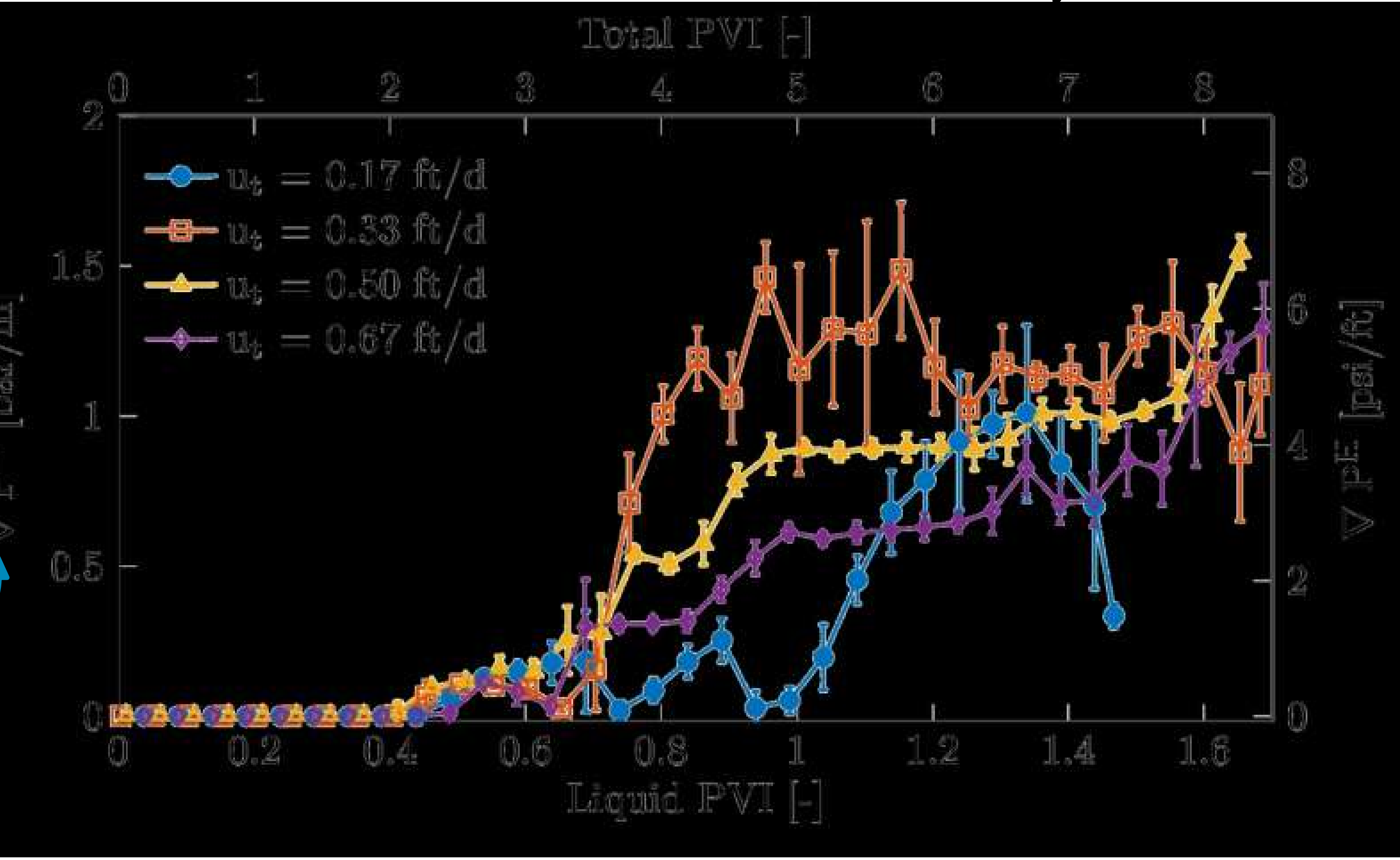


RESULTS

Effect of velocity

- ☐ Magnitude of pressure gradient is similar but that of fluctuations increases as velocity decreases.

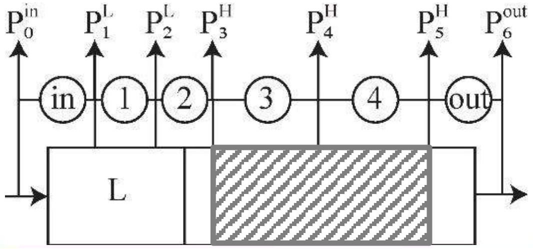


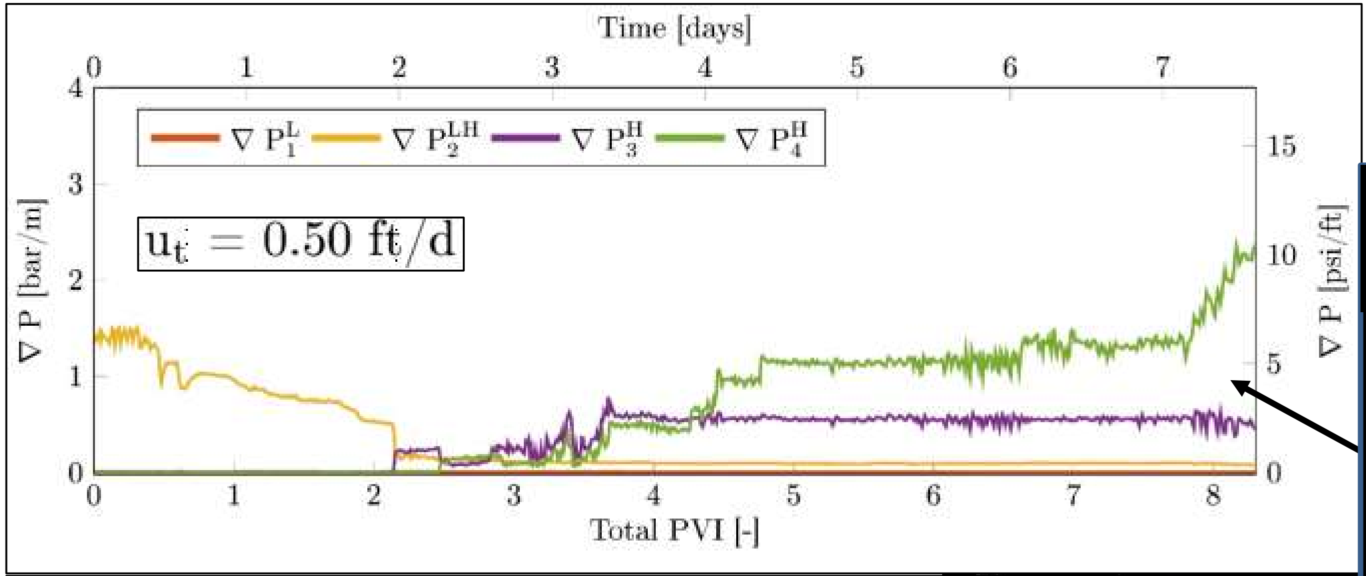


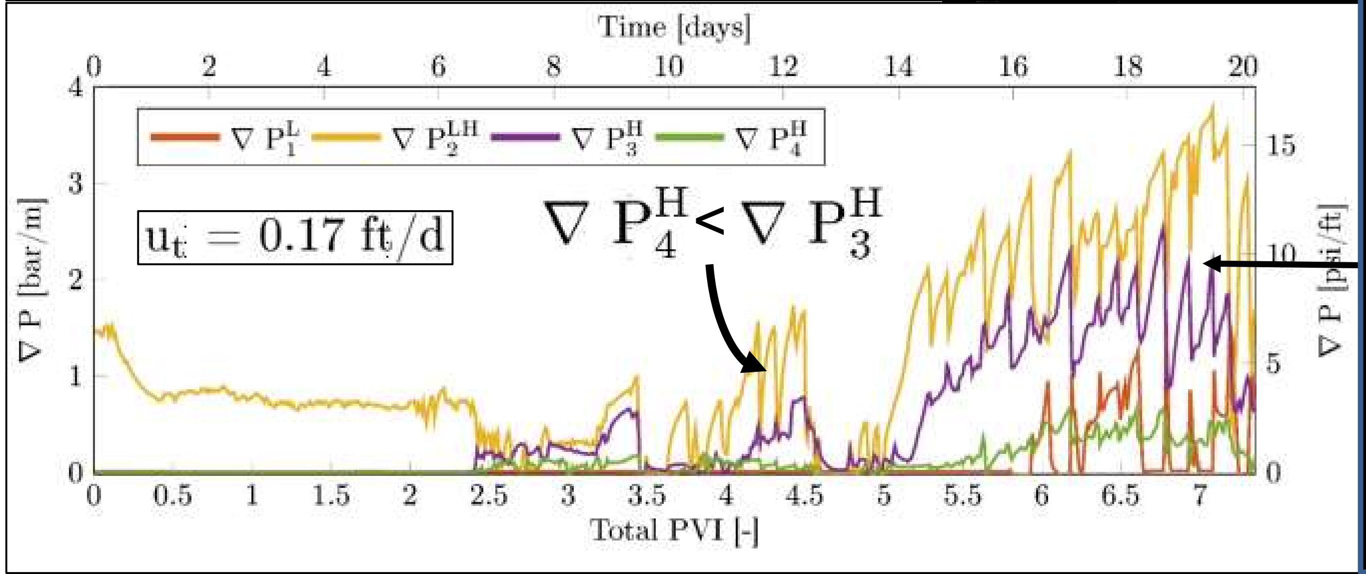
Shah, S.Y. et. al., SPE J., 2019

RESULTS

Effect of velocity





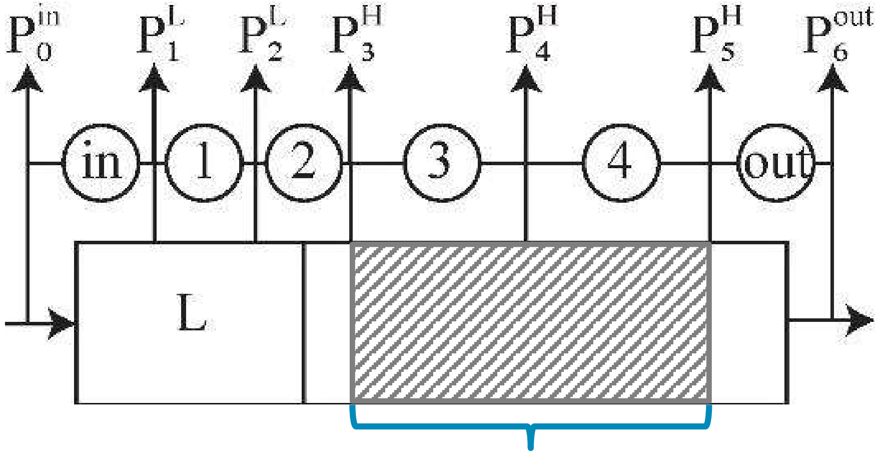


Observed weaker foam in outlet tubing at lower velocity.

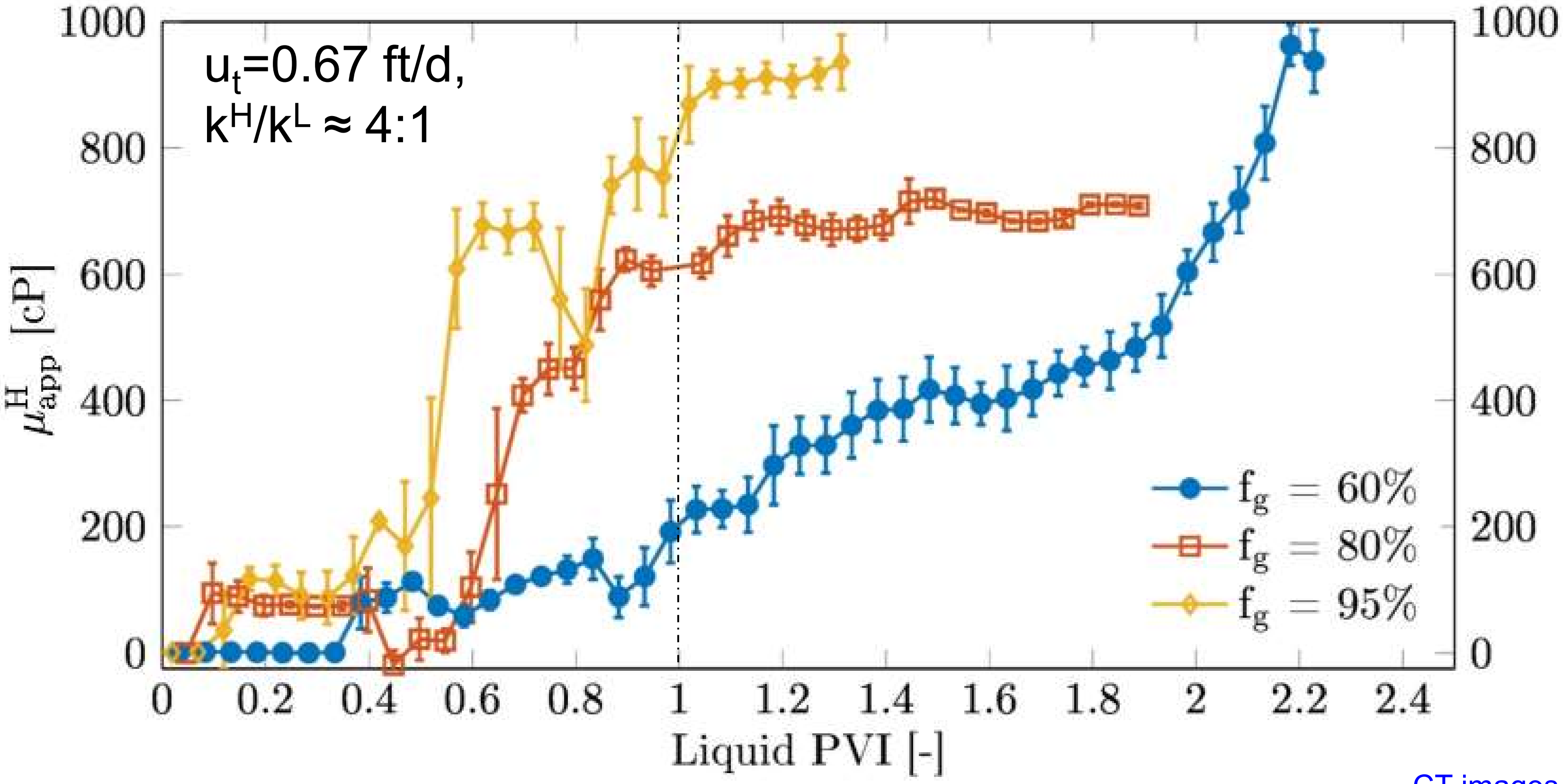
RESULTS

Effect of fractional flow

- ☐ No clear effect of f_g observed. At f_g<60%, foam was generated in the low-perm zone itself.



$$\mu_{app}^H = \frac{k^H \nabla P}{u_l + u_g}$$


u_t=0.67 ft/d,
$k^H/k^L \approx$ 4:1

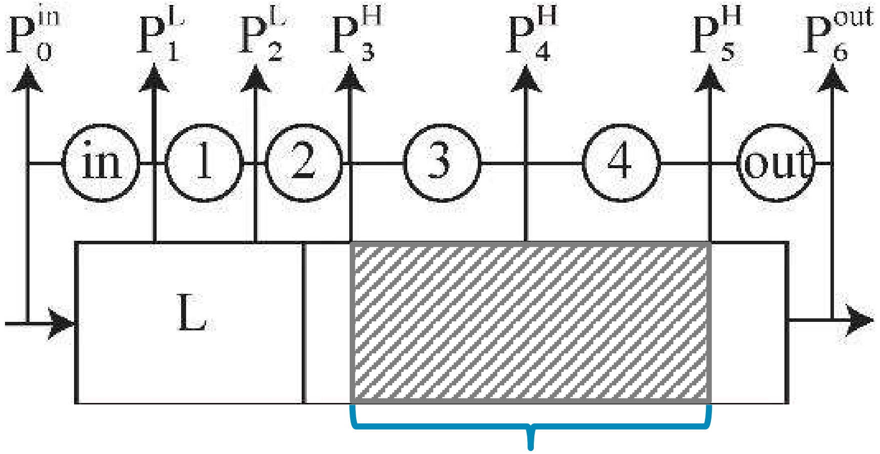
CT images

Shah, S.Y. et. al., SPE J., 2019

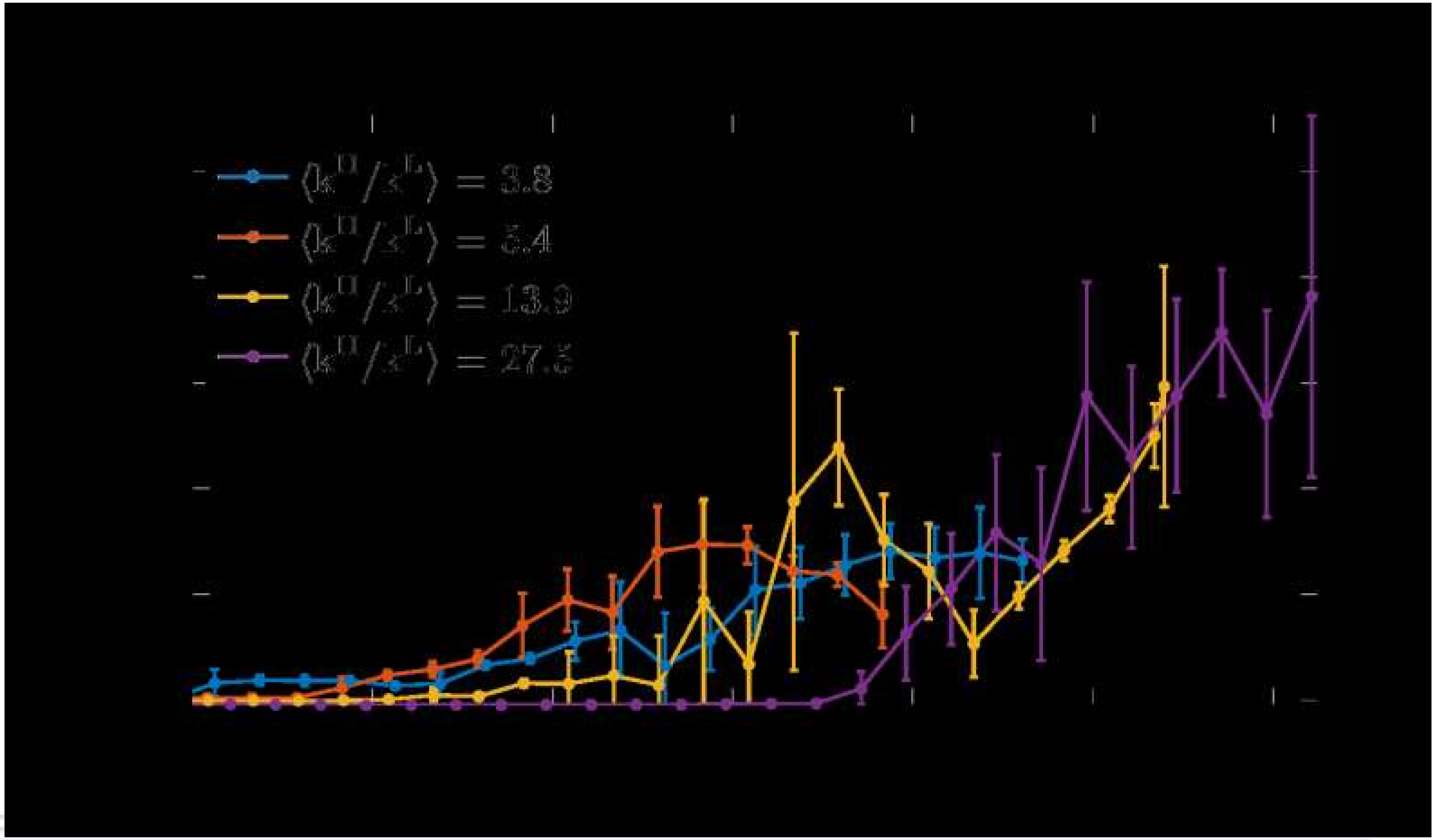
RESULTS

Effect of permeability contrast

- ☐ Foam strength appears to increase with increase in permeability contrast.



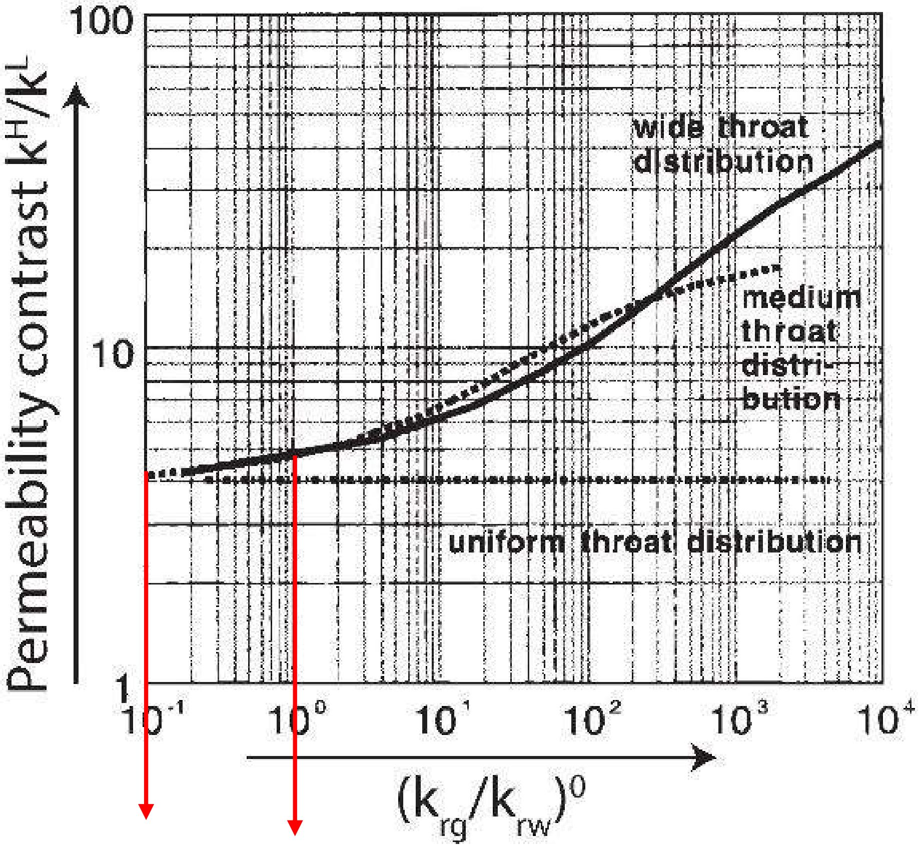
$$\mu_{app}^{H} = \frac{k^{H} \nabla P}{u_l + u_g}$$



Shah, S.Y. et. al., SPE J., 2018

CAN WE VALIDATE THEORETICAL RESPONSES?

- ❑ At a given permeability contrast, we observe foam generation in drier flows than predicted by theory.
- ❑ Effect of f_g unclear.

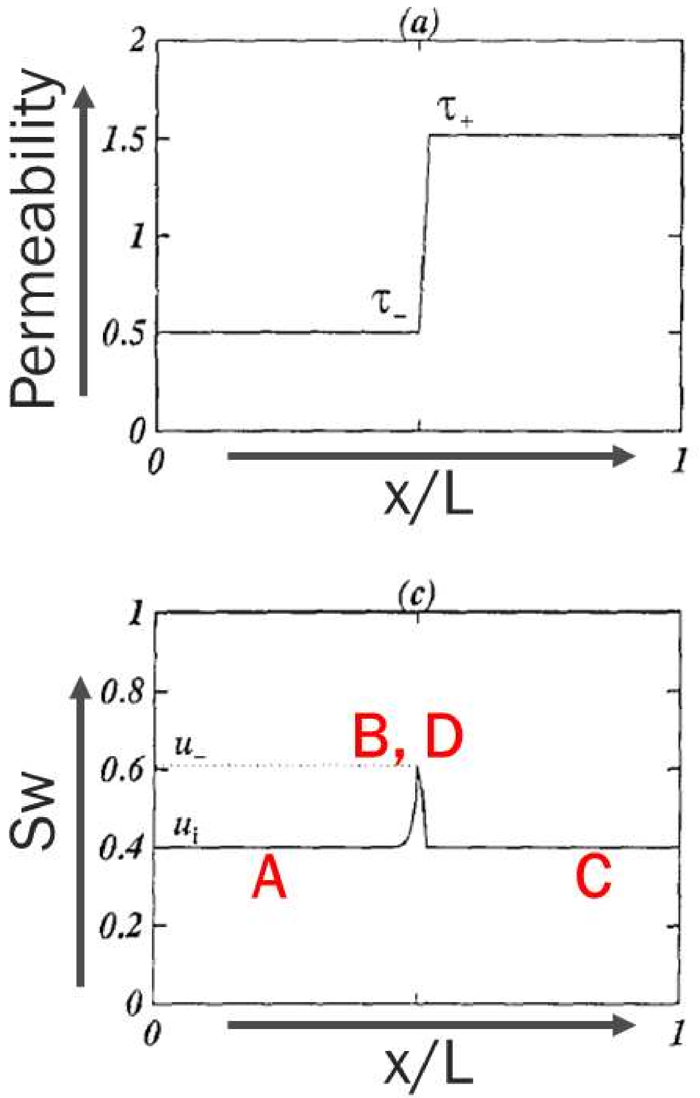


f_g=80% f_g=90%

Rossen, W.R., 1999

CAN WE VALIDATE THEORETICAL RESPONSES?

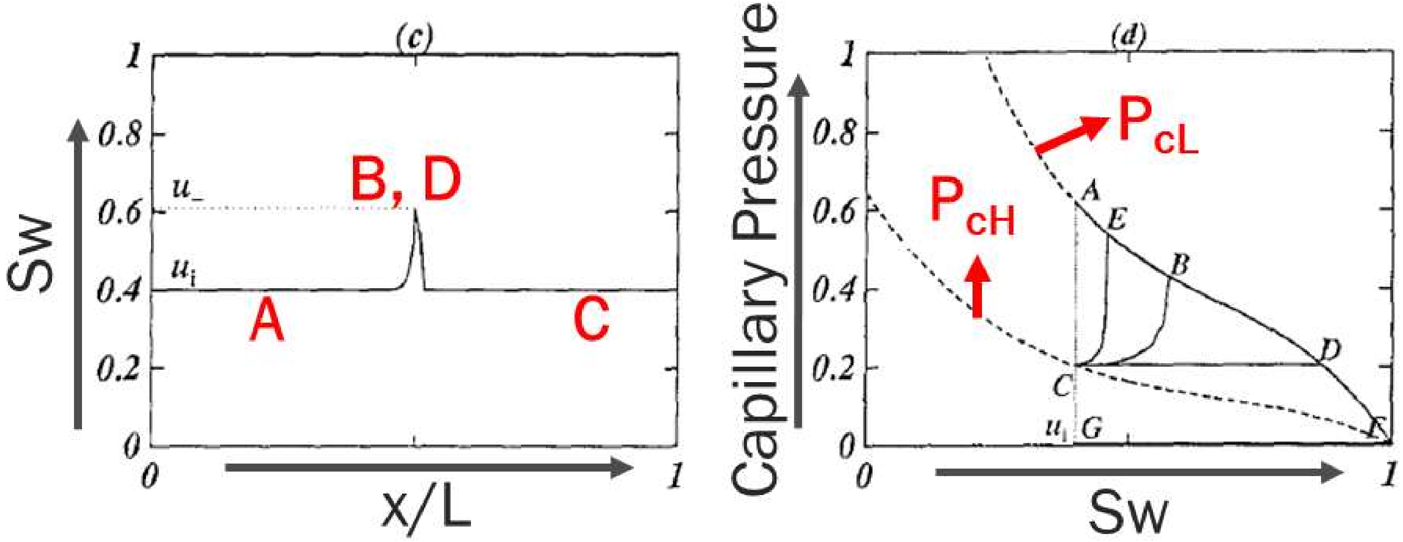
- Analytical saturation response to a sharp change in permeability (Yortsos and Chang, 1990)



CAN WE VALIDATE THEORETICAL RESPONSES?

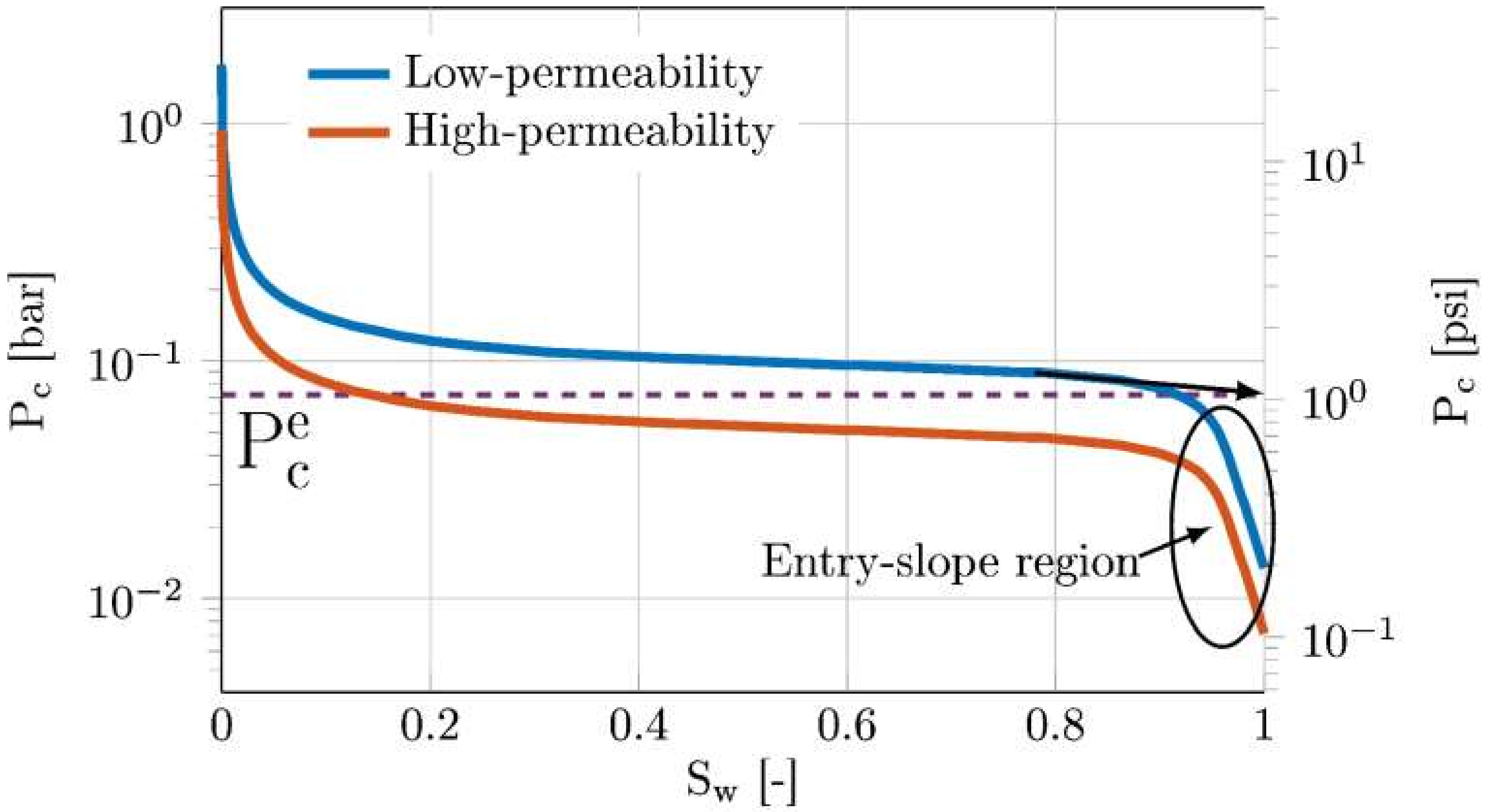
☐ Analytical saturation response to a sharp change in permeability (Yortsos and Chang, 1990)

☐ Falls, A.H. et al. (1988) estimated $P_c^{sn} \approx 1/2\, P_c^{e}$



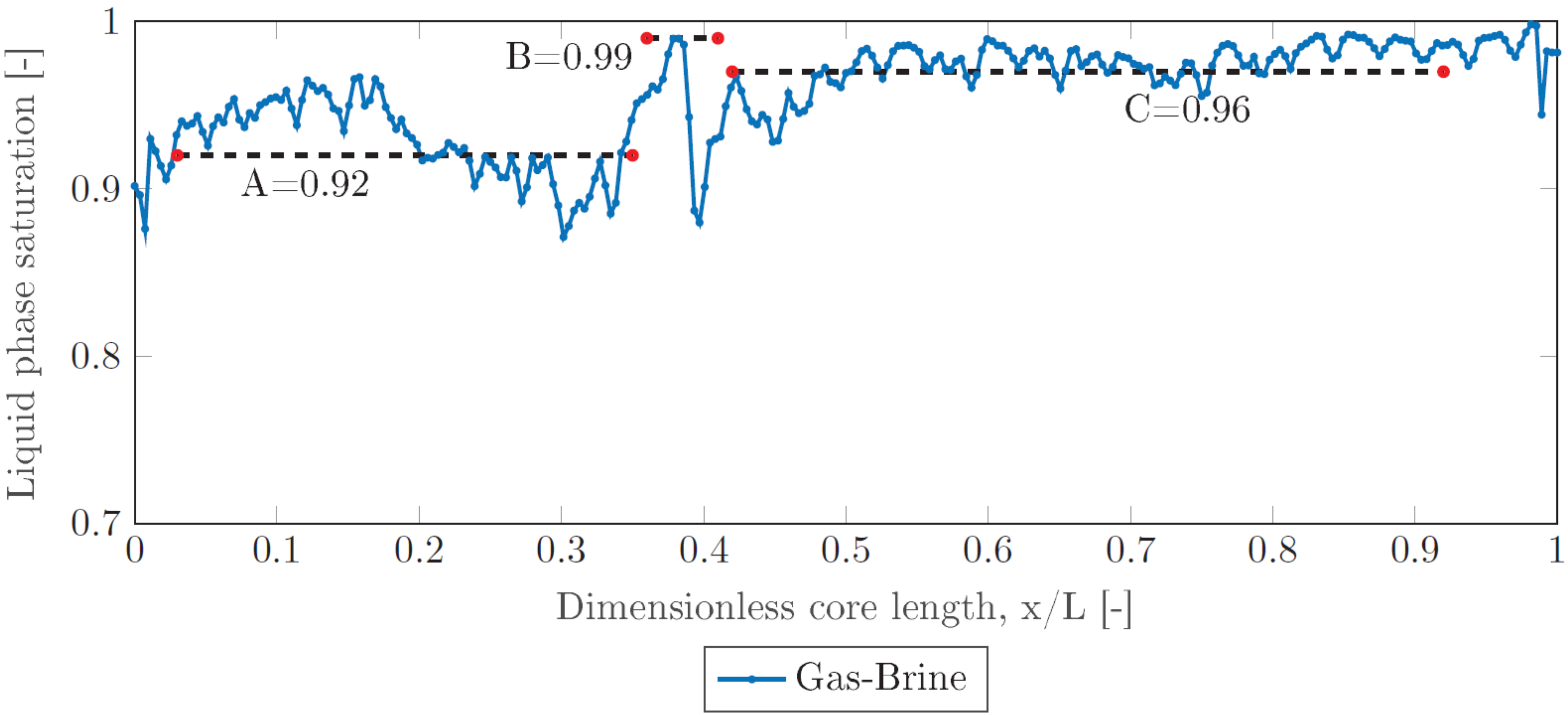
CAN WE VALIDATE THEORETICAL RESPONSES?

- ☐ We obtained P_c curves for sintered glass porous media from Berg et al. (2014).
- ☐ These curves were extended to the petrophysical and fluid properties of our system.



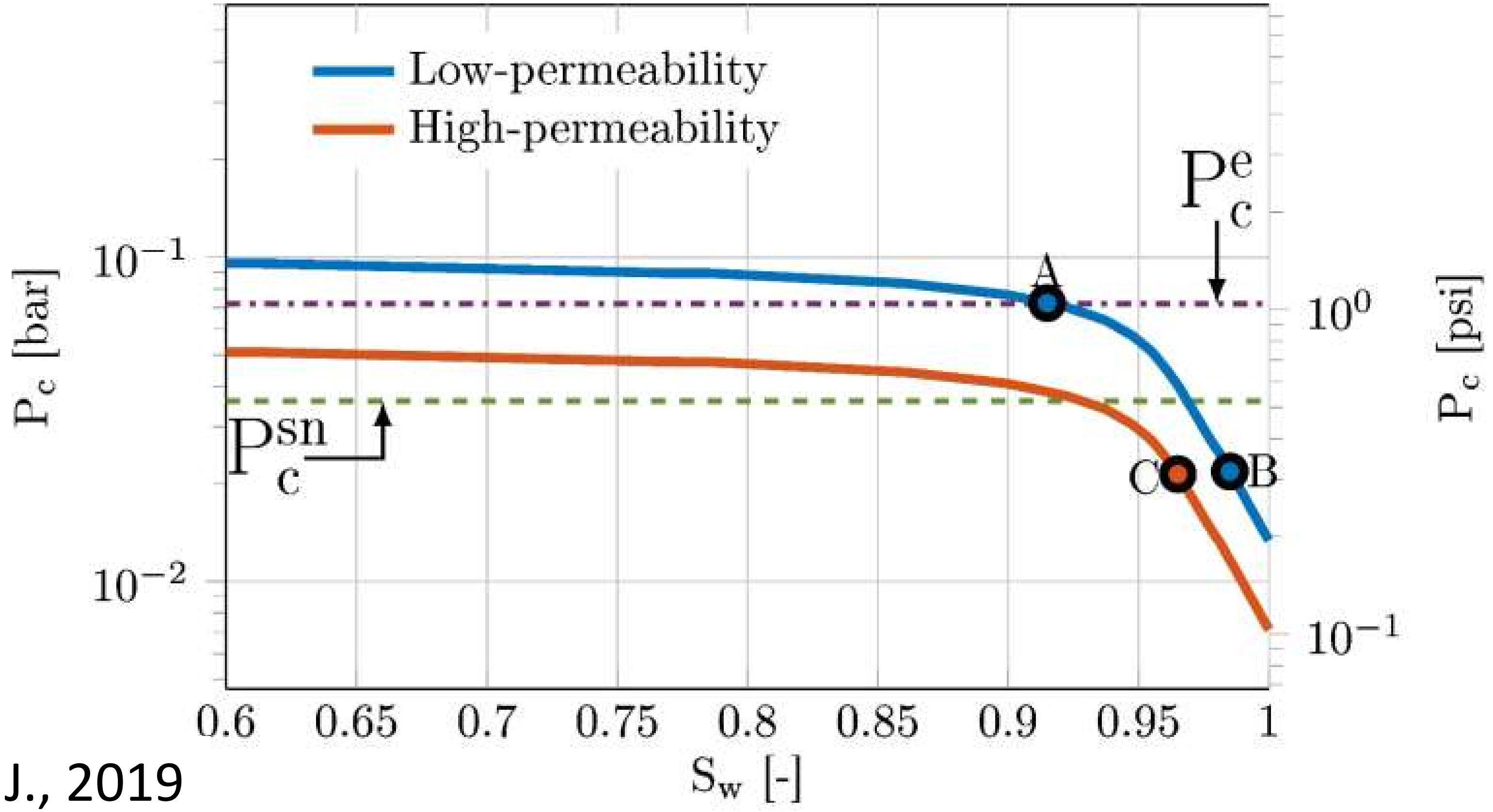
CAN WE VALIDATE THEORETICAL RESPONSES?

☐ Phase saturations extracted from CT results (sensitive to CT error and slice width).



CAN WE VALIDATE THEORETICAL RESPONSES?

- ☐ $P_c < P_c^{sn}$ ($\approx 1/2\ P_c^e$) at the boundary of the low-permeability zone.
- ☐ Foam generation is observed as soon as surfactant reaches the boundary.



Shah, S.Y. et. al., SPE J., 2019

SUMMARY

☐ Demonstrated foam generation across a sharp increase in permeability.

☐ Demonstrated propagation at field-like velocities (< 1ft/d).

☐ Reduced λ_g high-permeability zone (benefits sweep efficiency away from wells).

☐ Foam generation triggered as soon as surfactant reaches the boundary.

SUMMARY

- Foam strength higher with greater permeability contrast.

- Foam generation takes longer across greater permeability contrast.

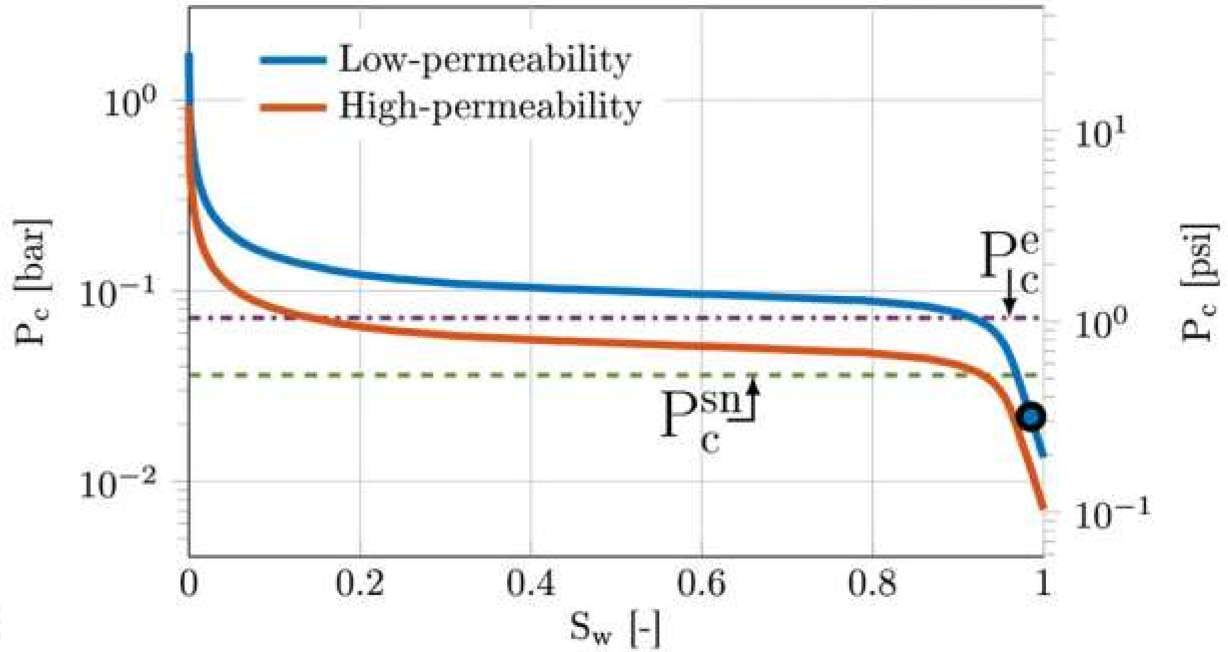
- No clear effect of f_g in range of conditions studied.

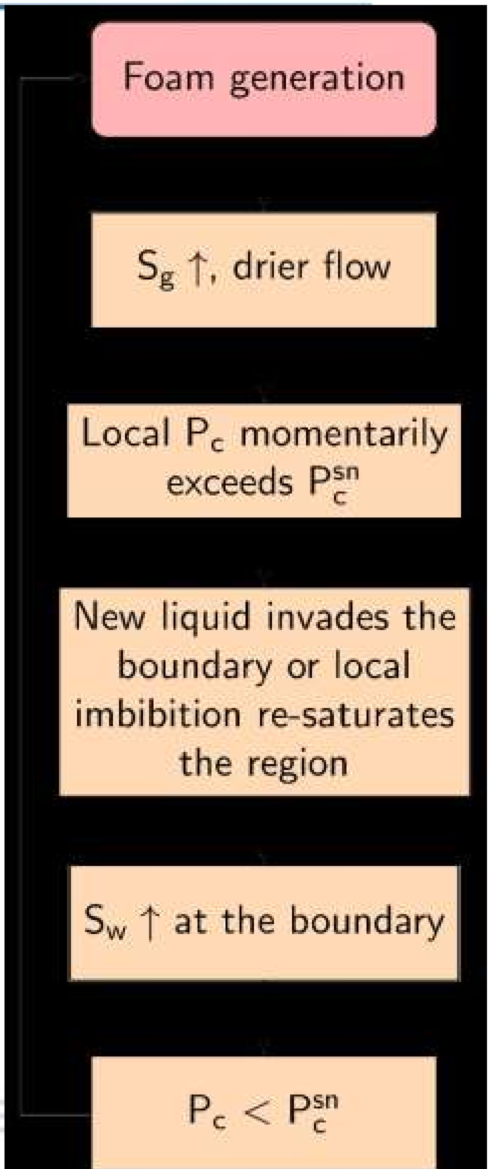
- Some theoretical responses verified and some inconsistencies observed.

SUMMARY

☐ This process is intermittent (also reported by Falls et al., 1988).

☐ Intermittency greater with greater k^H/k^L, higher f_g and lower u_t.





Foam generation

S_g ↑, drier flow

Local P_c momentarily exceeds P_c^{sn}

New liquid invades the boundary or local imbibition re-saturates the region

S_w ↑ at the boundary

$P_c < P_c^{sn}$

WHAT DOES IT MEAN FOR THE FIELD?

- ☐ Implications for the field:
  - ☐ Foam generation deep in the reservoir
  - ☐ Propagation even at field-like superficial velocities
  - ☐ Foam generates in the high-permeability layers, blocks flow and reduces:
    - λ_V
    - Extent of gravity segregation
  - ☐ Reduced cross-flow
  - ☐ Improved reservoir scale sweep efficiency

THANK YOU

ACKNOWLEDGEMENTS

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Marc Friebel

Karel Heller

Joost van Meel

Jens van den Berg

Jolanda van Haagen-Donker

TU Delft

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