CO_2 Foam EOR, Mobility Control

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Challenges of CO_2 Mobility Control in Middle East

- High temperatures: >100 ◦C
- High Salinity: > 20% ppm TDS
- High MMP: >3,000 psi
- Carbonate formations

Outline of Presentation

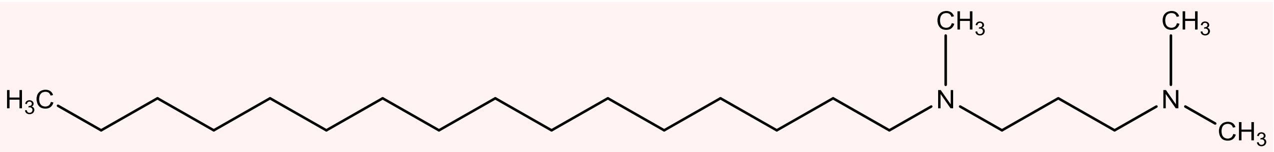
- **Surfactant stability and adsorption**
- **In situ foam generation by co-injection and SAG**
- **Estimation of foam parameters for simulation**
  - **Foam dry-out**
  - **Shear thinning**
  - **Surfactant concentration**
  - **Effect of crude oil**
- **Simulation of oil displacement in heterogeneous reservoir**
- **Conclusions**

Surfactant Stability & Adsorption

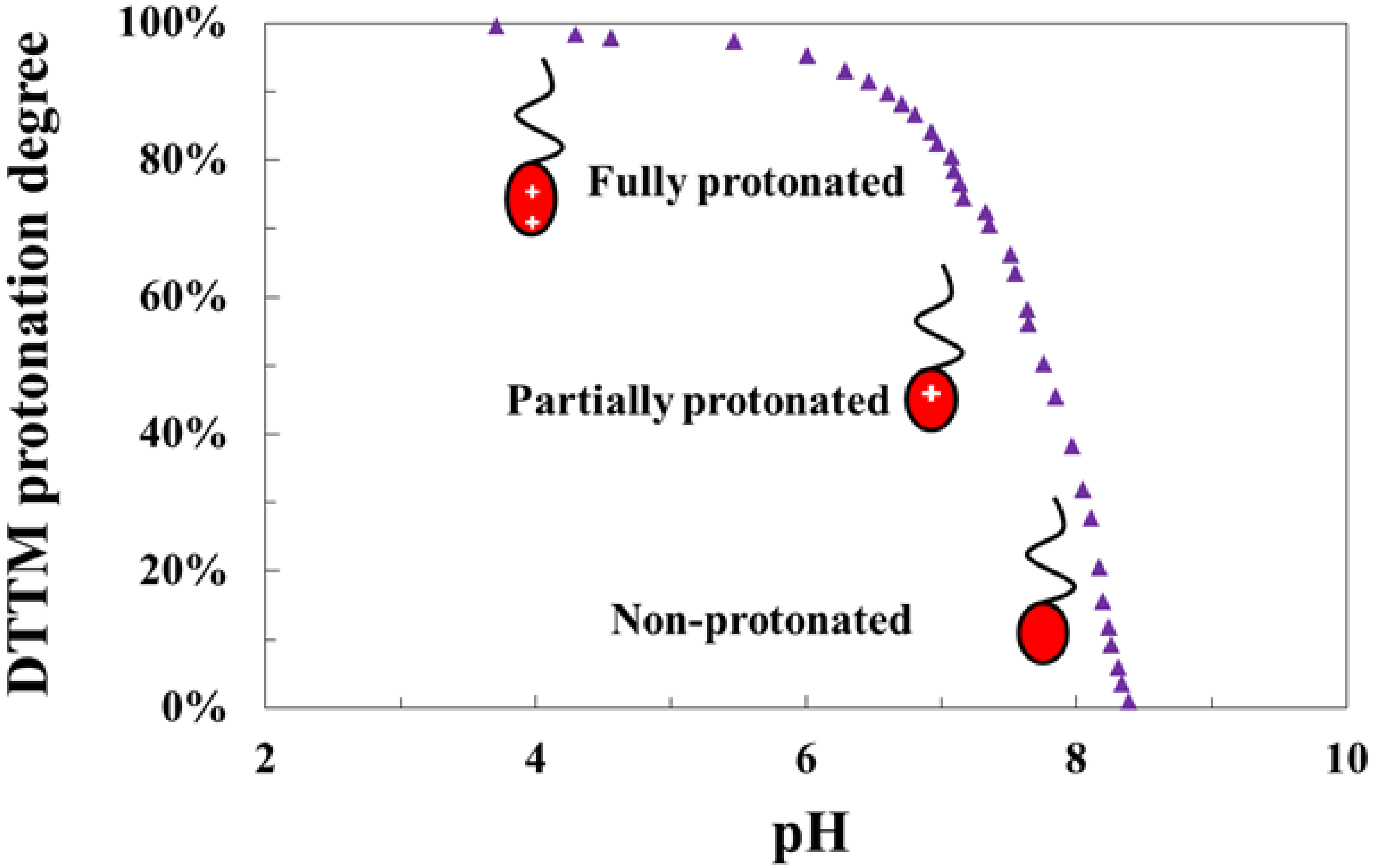
- Anionic surfactant – Excessive adsorption on carbonates
- Nonionic surfactant – Above cloud point temperature
- Switchable cationic, Ethomeen C/12* – Minimum pressure gradient for foam generation
- Duomeen TTM* – Evaluated here

* Trademark of AkzoNobel

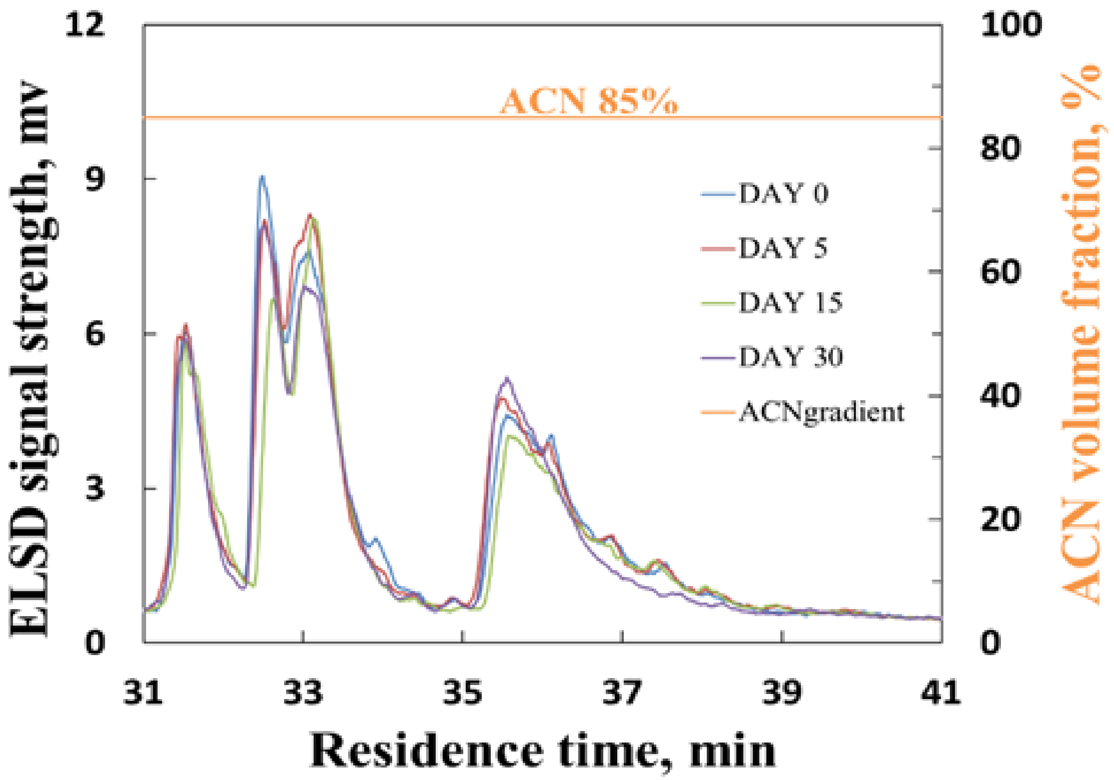
TTM is fully protonated at the pH of CO_2 saturated brine



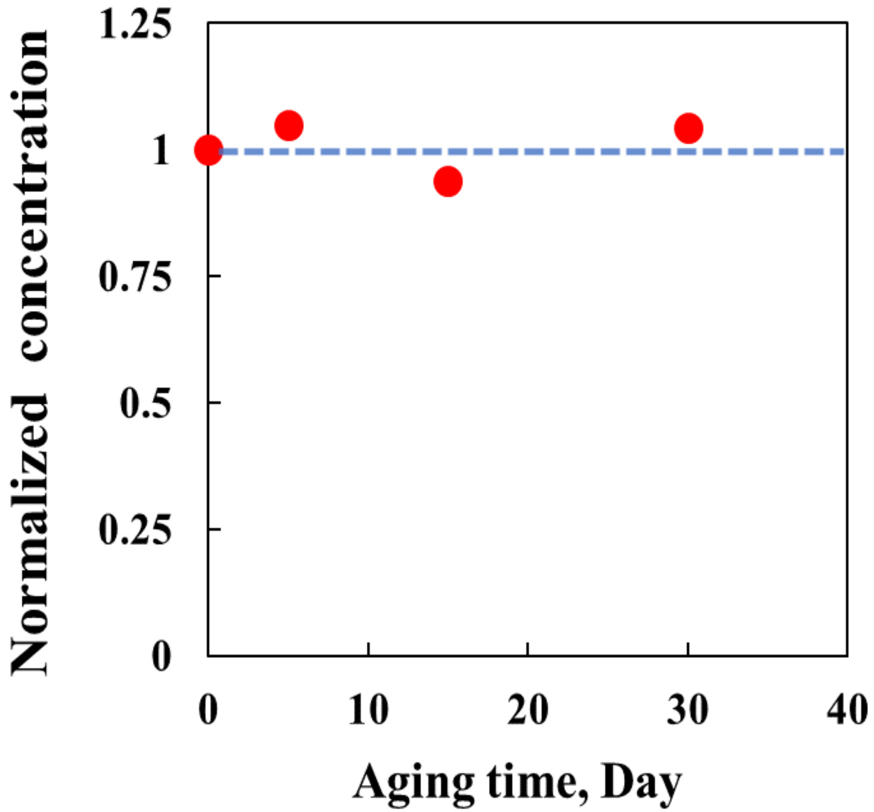
$$C_{16\text{-}18}N(CH_3)C_3N(CH_3)_2 + 2H^+ \leftrightarrow C_{16\text{-}18}N^+H(CH_3)C_3N^+H(CH_3)_2$$



TTM is stable at 120 ◦C in presence of oxygen scavenger

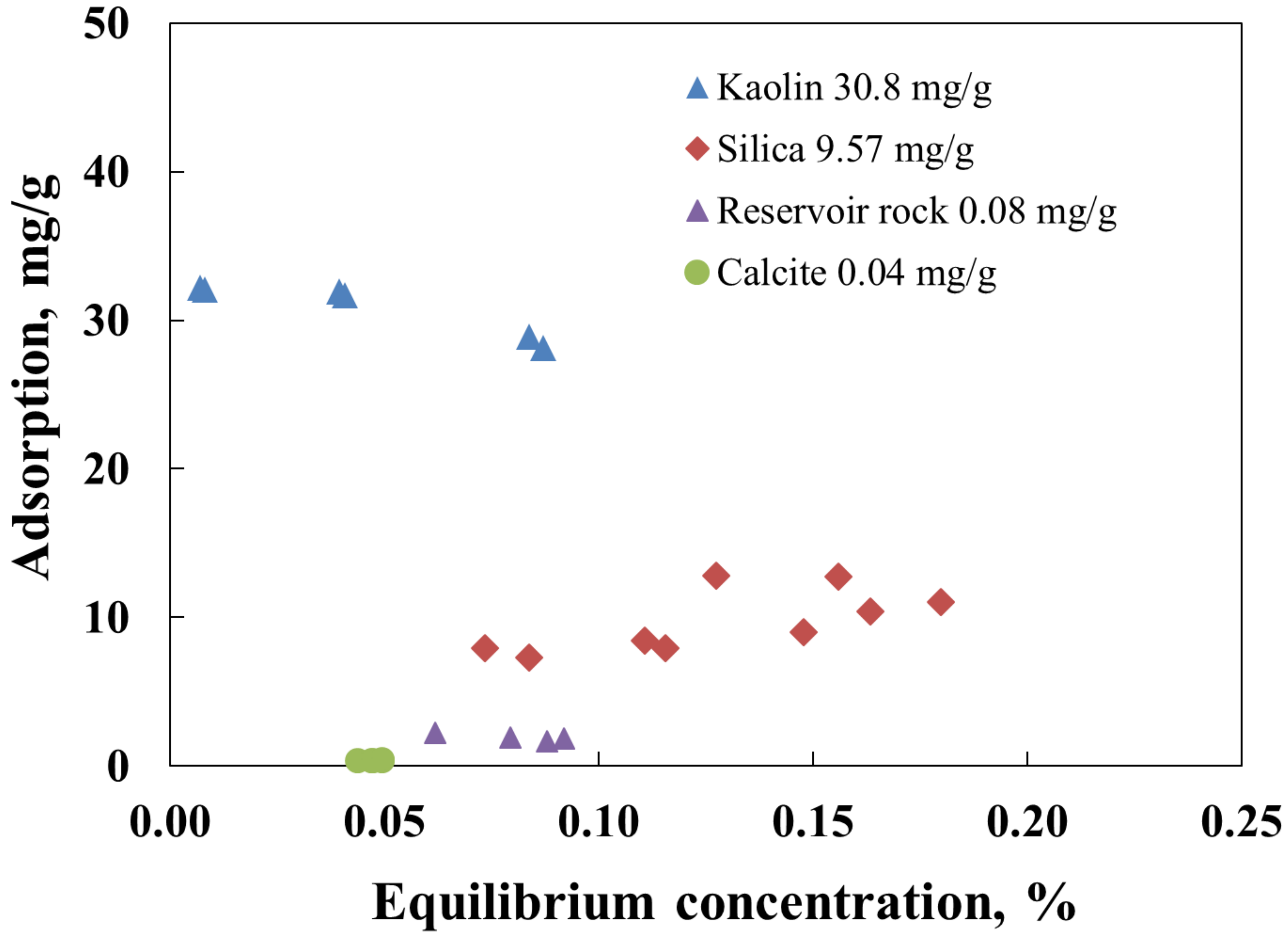


1 DTTM characteristic peaks and signal strength as a function of aging time at 120℃, Formation Brine, pH4, and reducing conditions.

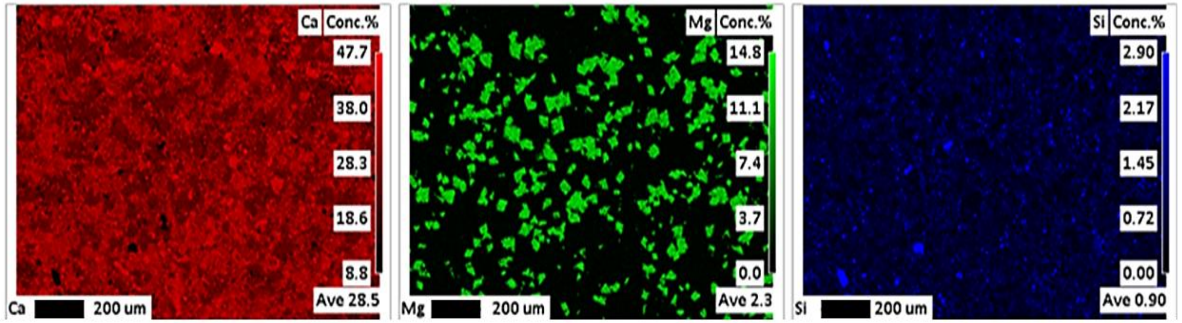


DTTM signal integral area as a function of aging time, the areal variation is within the detection error.

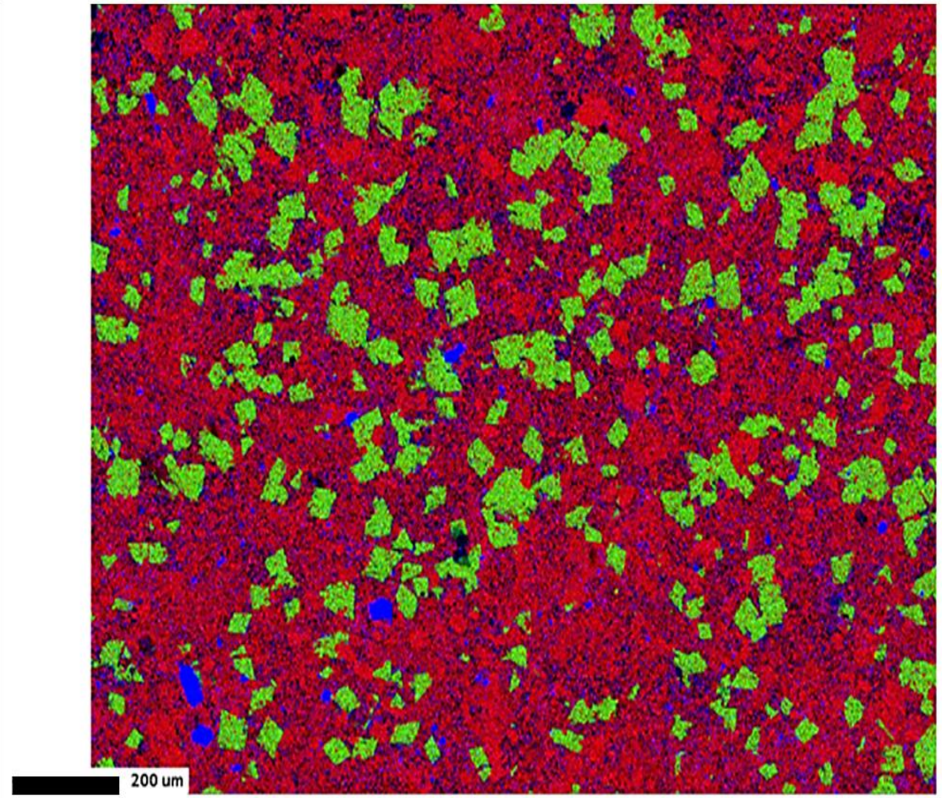
Measured Adsorption of TTM



Elemental Composition of Reservoir Rock



Ca 25%, Mg 2.8%, Si 0.7%



Red – Ca
Green – Mg
Blue - Si

In situ foam generation without oil

3,400 psi,

120 °C.

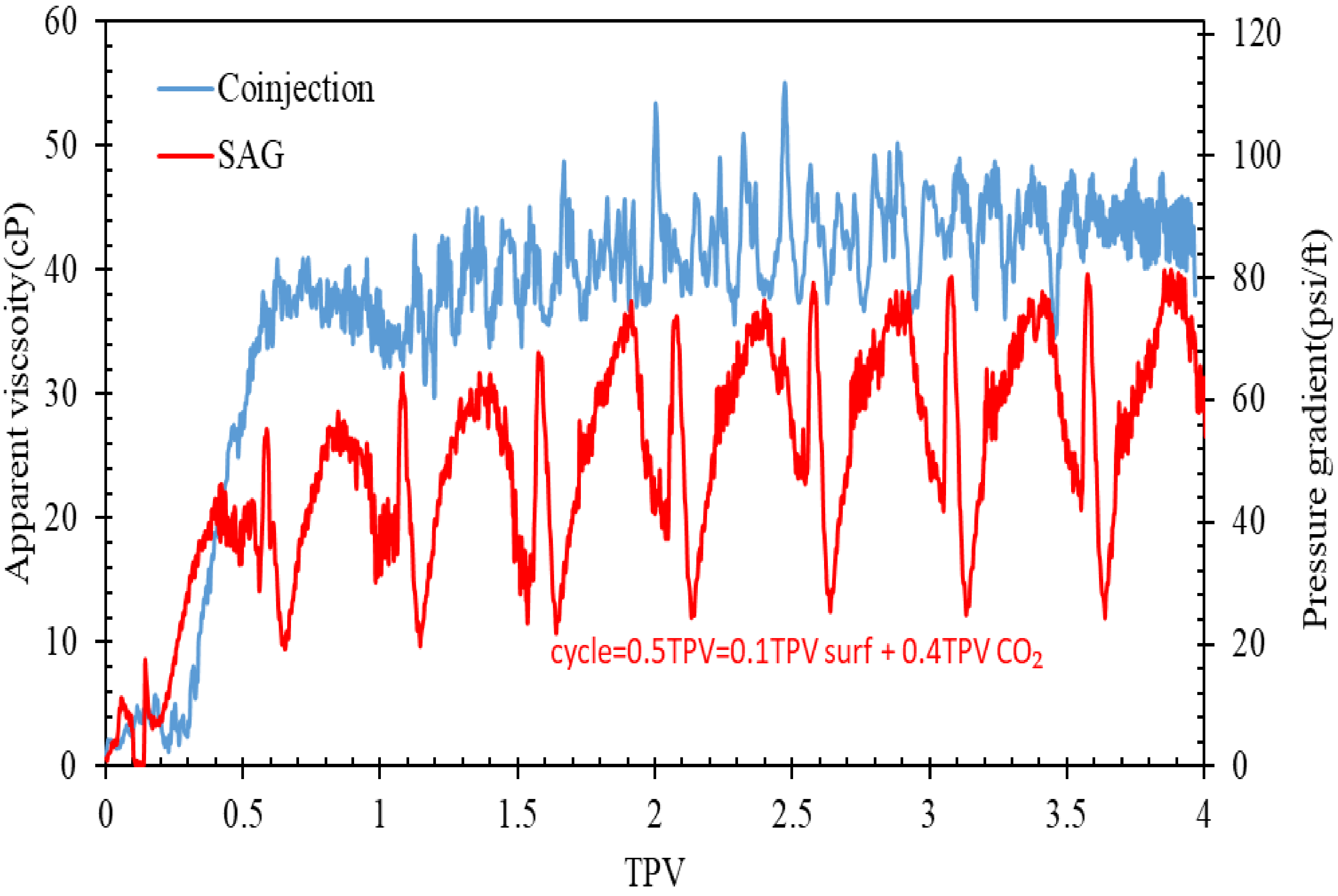
Foam quality=80%,

4ft/day

1% TTM in 22% TDS Brine,

L*D=3*1.5 inches,

k=321 mD

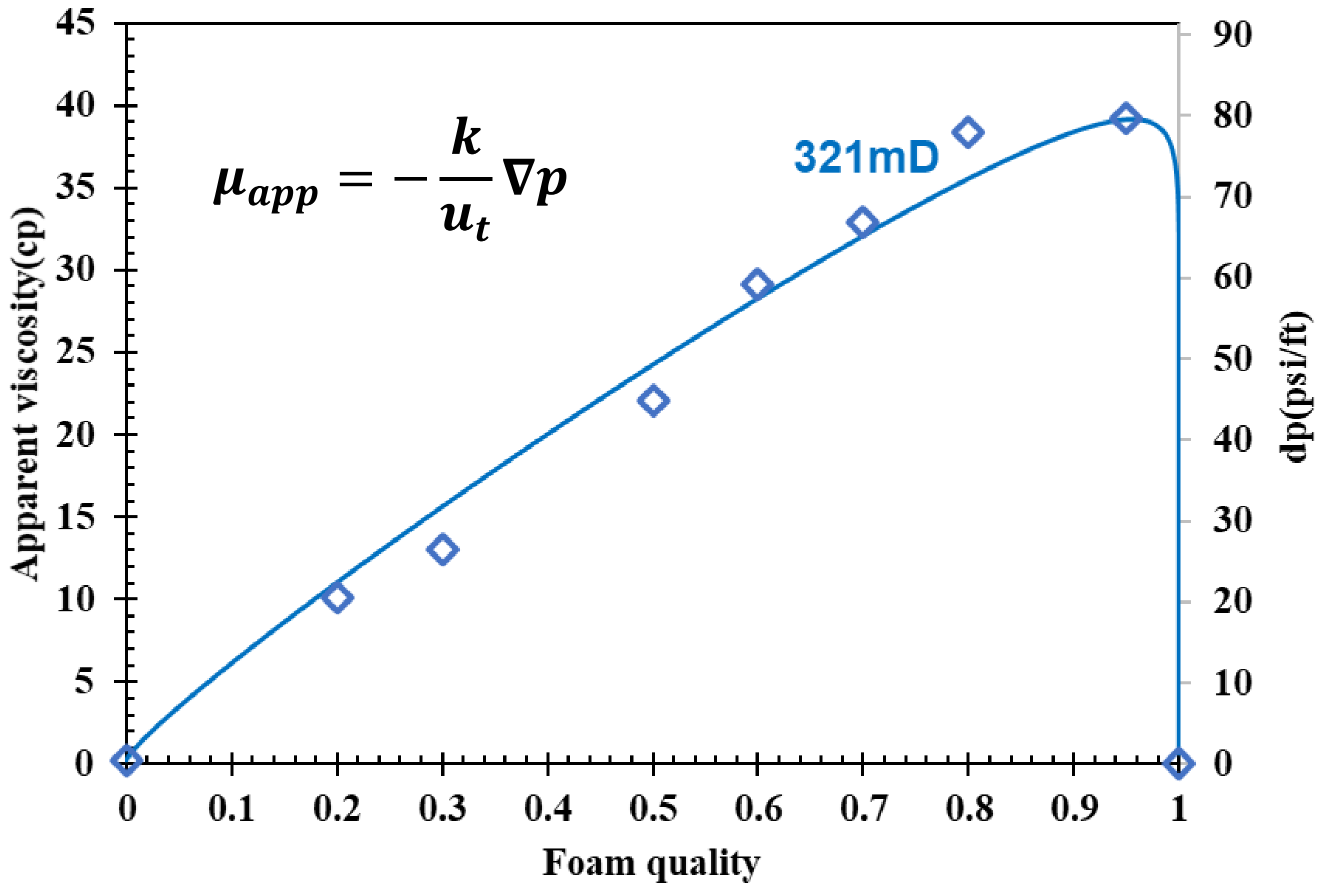


Dry-out function parameters(1%TTM)

$$FM = \frac{1}{1 + fmmob \times \{0.5 + \frac{arctan[epdry(S_w - fmdry)]}{\pi}\}}$$

$k(mD)$	$fmmob$	$epdry$	$fmdry$
321	188	70	0.238

Experiment and STARS model(1% TTM)



$$f_g = \frac{u_g}{u_w + u_g} = \frac{u_g}{u_t}$$

Experimental conditions

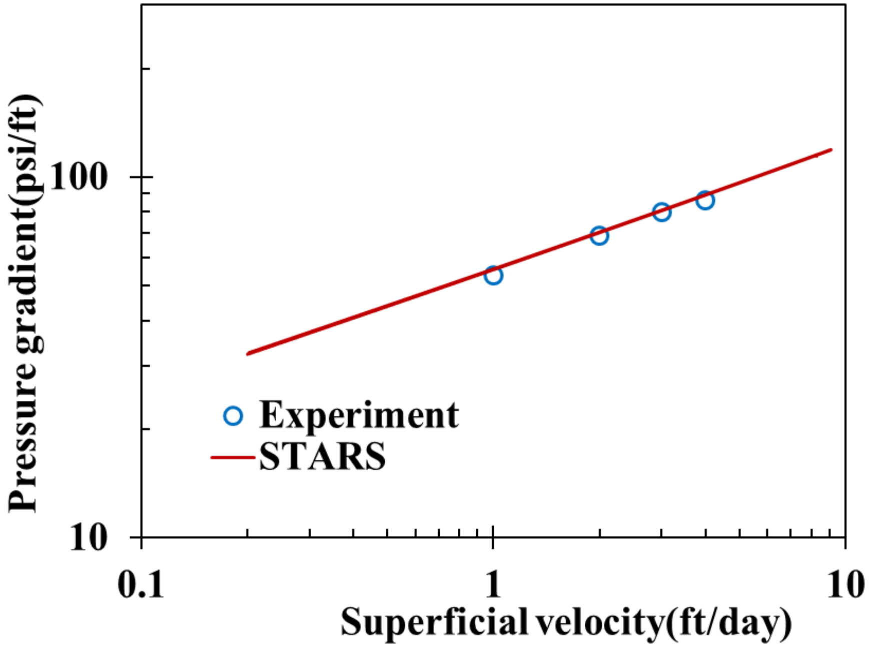
- 1% TTM, pH=7
- 120 °C
- 3,400 psi
- 4 ft/day
- Indiana Limestone(321mD)

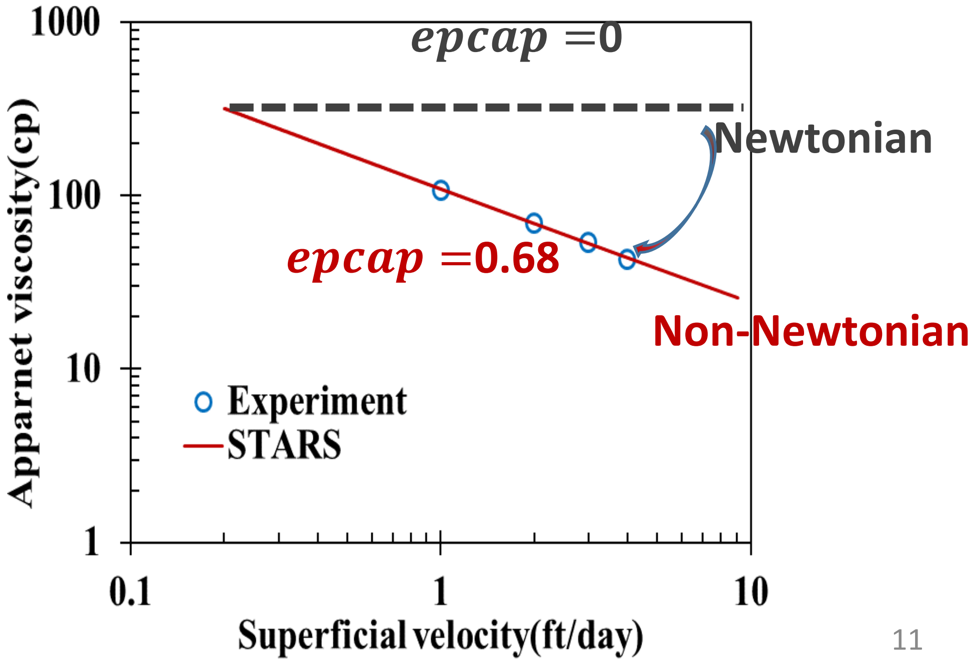
Shear thinning parameters

$$\boldsymbol{FM} = \frac{1}{1 + fmmob \times Fwater \times \left(\frac{fmcap}{NCa}\right)^{epcap}}$$

$fmcap$	$epcap$
1.17e-06	0.68

Experimental conditions
- **1% TTM, pH=7**
- **120 °C**
- **3,400 psi**
- **1~4 ft/day**
- **fg=0.8**
- **Indiana Limestone(321mD)**



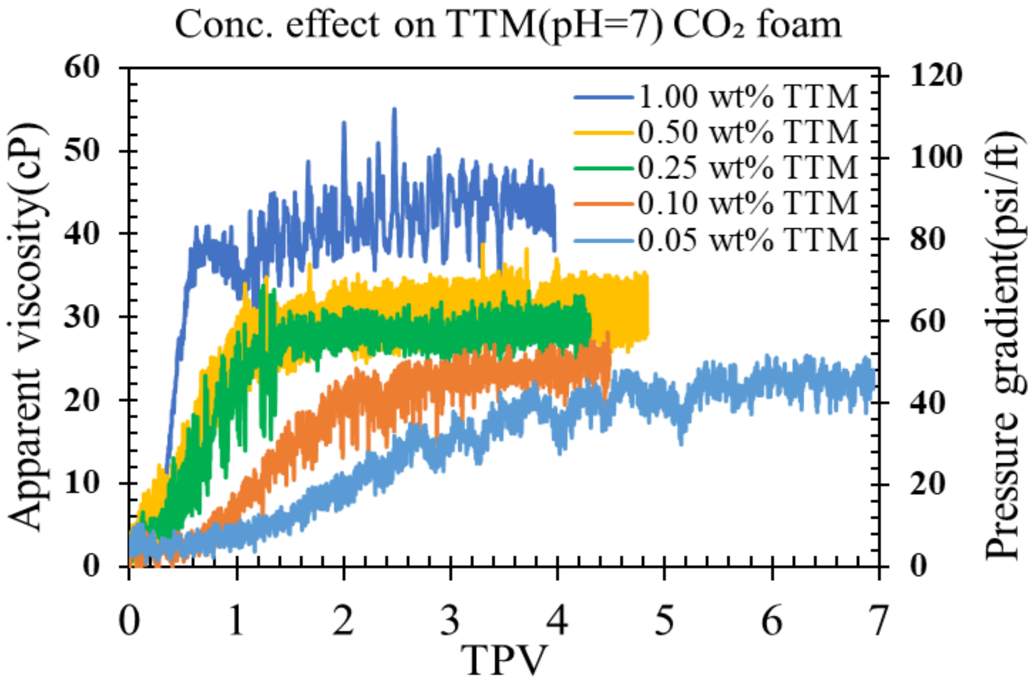


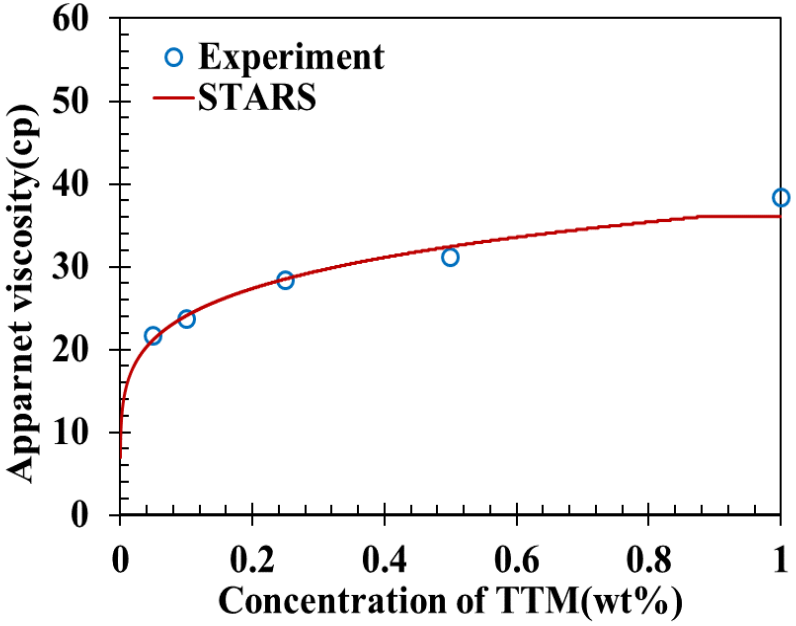
Surfactant concentration parameters

$$\boldsymbol{FM} = \frac{1}{1 + fmmob \times Fwater \times \left(\frac{Csw}{fmsurf}\right)^{epsurf}}$$

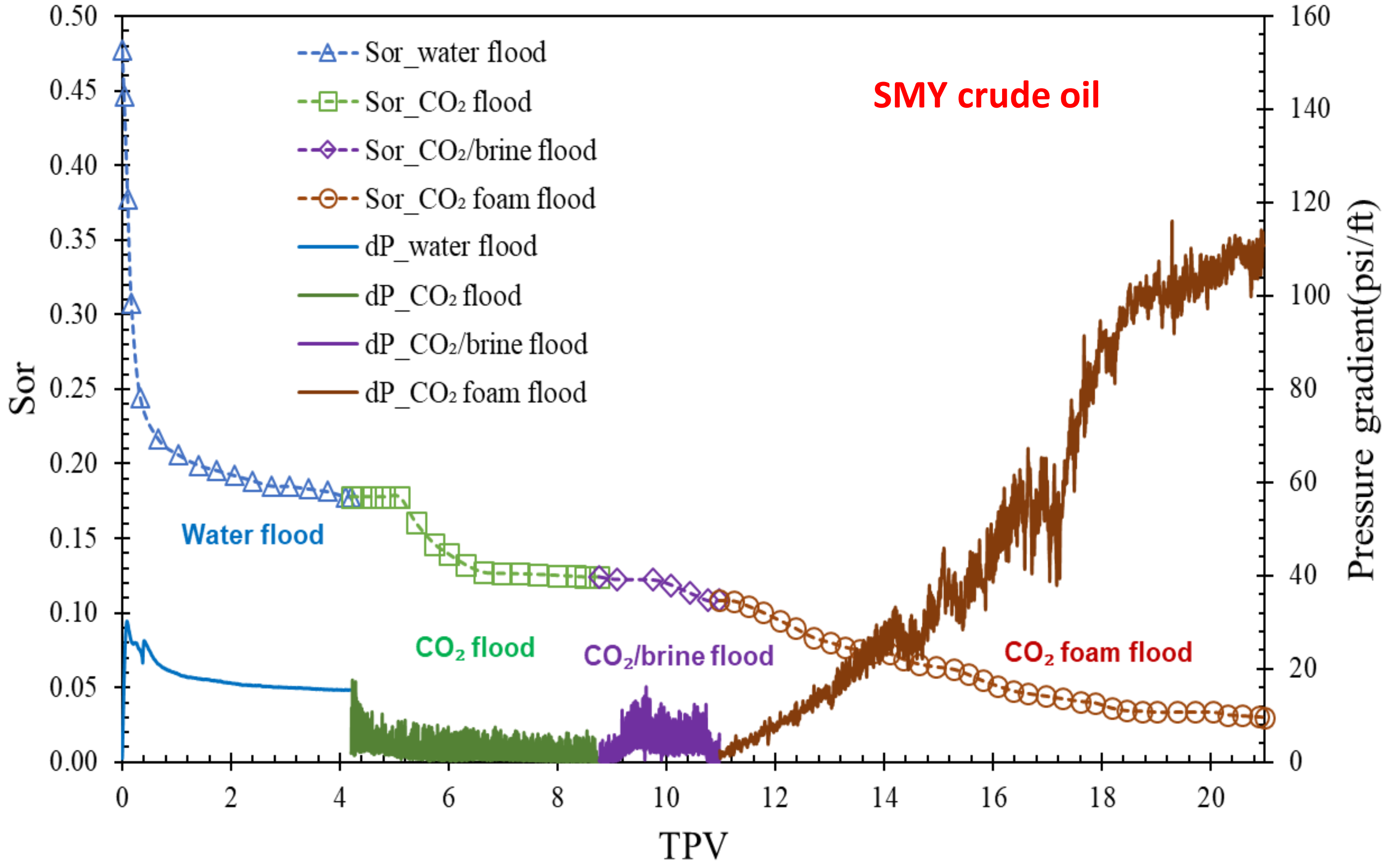
$fmsurf$	$epsurf$
0.89 wt%	0.195

Experimental conditions
- **0.1~1% TTM, pH=7**
- **120 °C**
- **3400 psi**
- **4 ft/day**
- **fg=0.8**
- **Indiana Limestone(321mD)**





CO_2 foam EOR by TTM

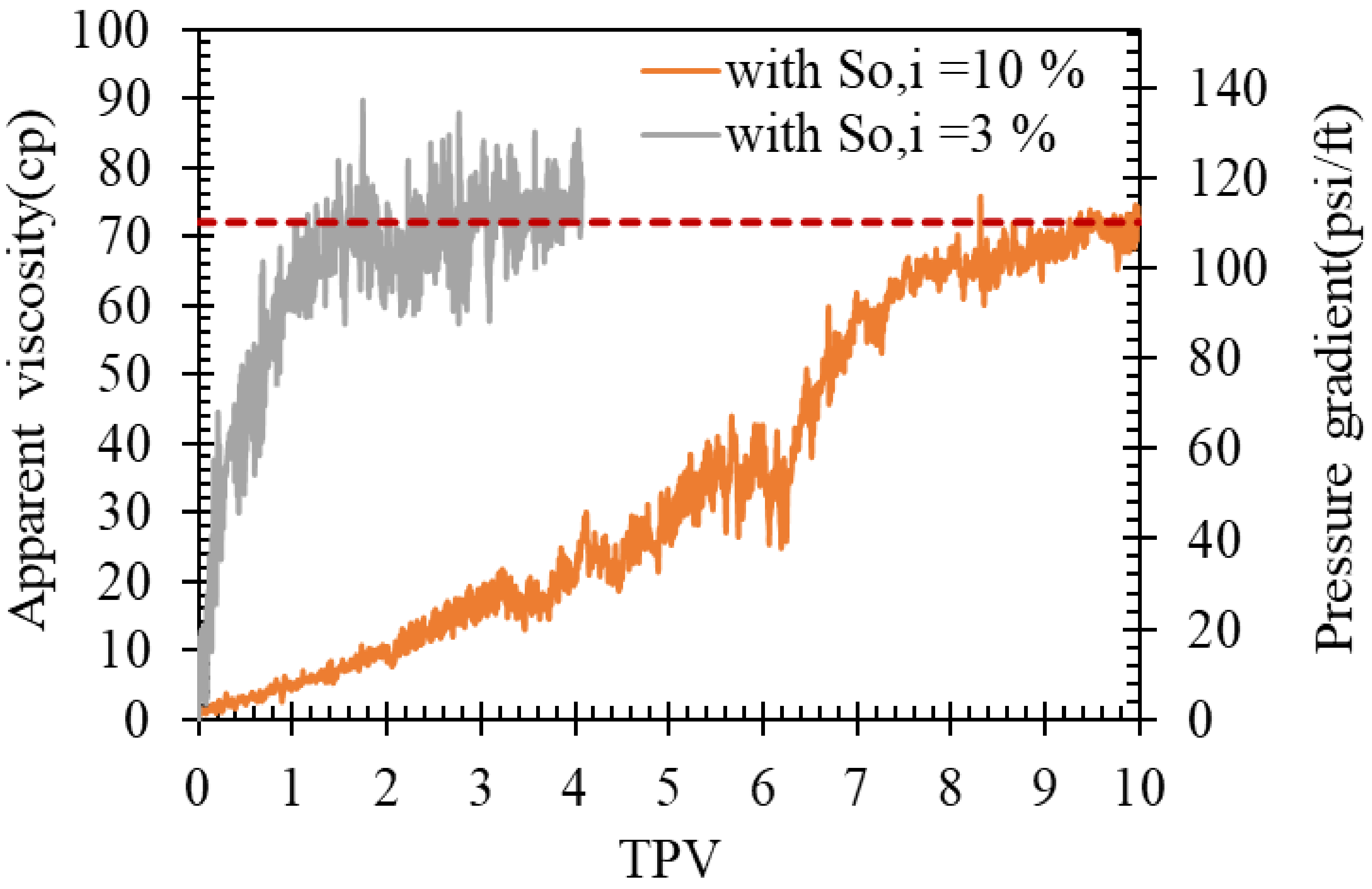


Oil saturation and pressure gradient for water, CO_2, CO_2-brine, and CO_2 foam flooding in an Indiana limestone core

Experimental conditions

- **k=413 mD (L*D=6*1.5 inch)**
- **4ft/day**
- **fg=0.8**
- **1 wt% TTM**
- **120°C**
- **3400 psi**
- **SMY crude oil**

Effect of crude oil saturation on CO2 foam generation



CO_2 foam apparent viscosity at an initial crude oil saturation of 3% (grey) and 10% (orange) in an Indiana limestone core

Experimental conditions

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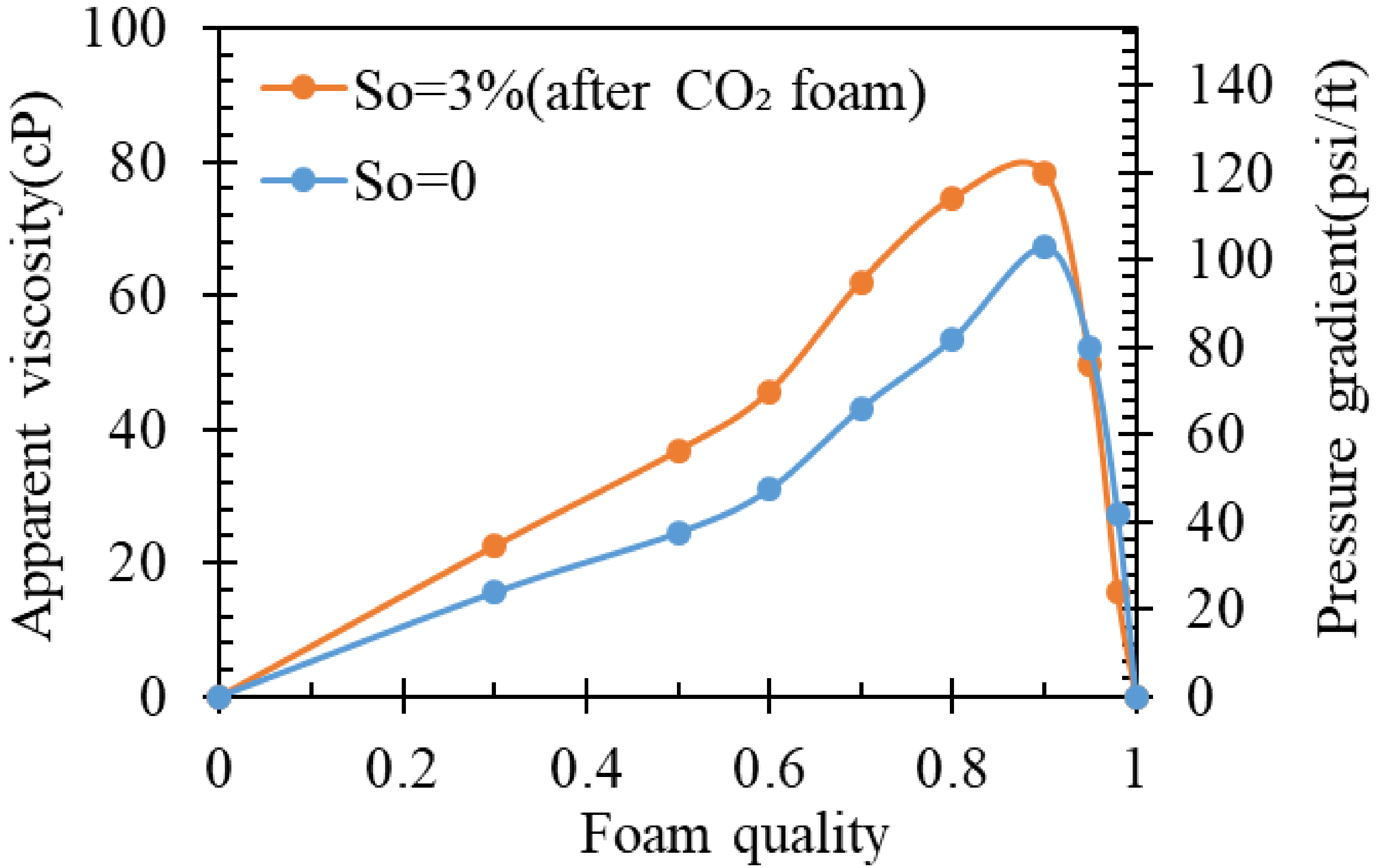
- **120^{o}C**
- **3400 psi**
- **SMY crude oil**

Effect of residual oil saturation on CO2 foam quality scan



<u>Experimental conditions</u>

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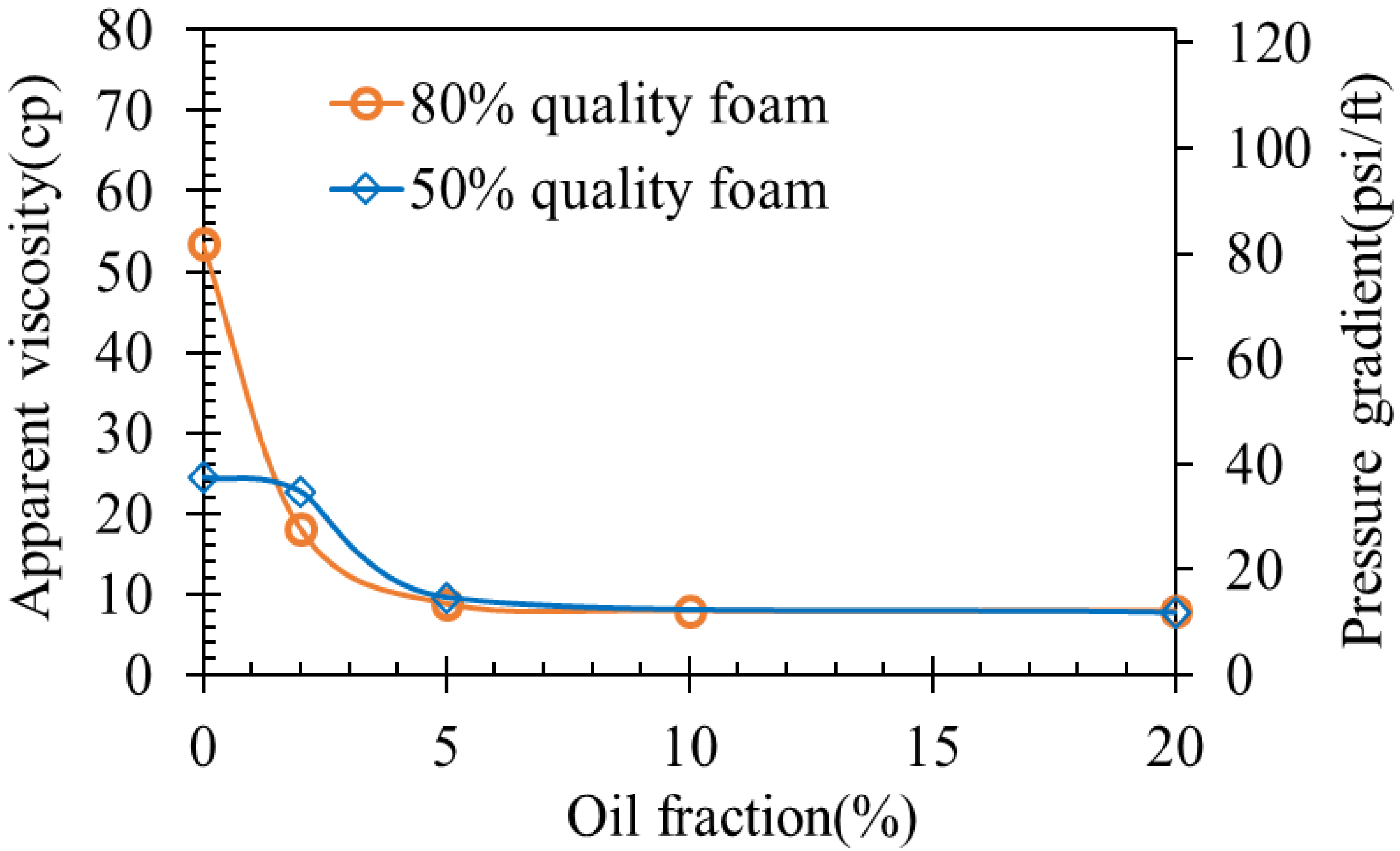
- 120°C
- 3400 psi
- •SMY crude oil

A CO_2 foam quality with 1 wt% TTM scan without oil and with 3% crude oil present, in an Indiana limestone core

Effect of oil fractional flow on foam strength



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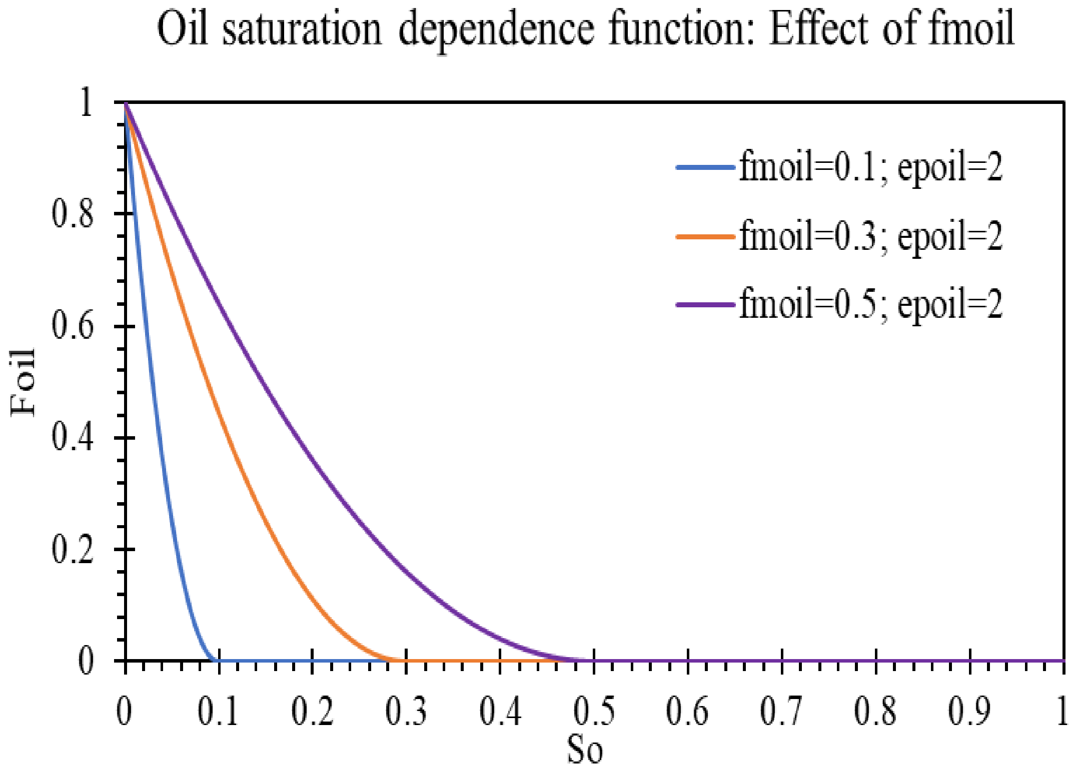
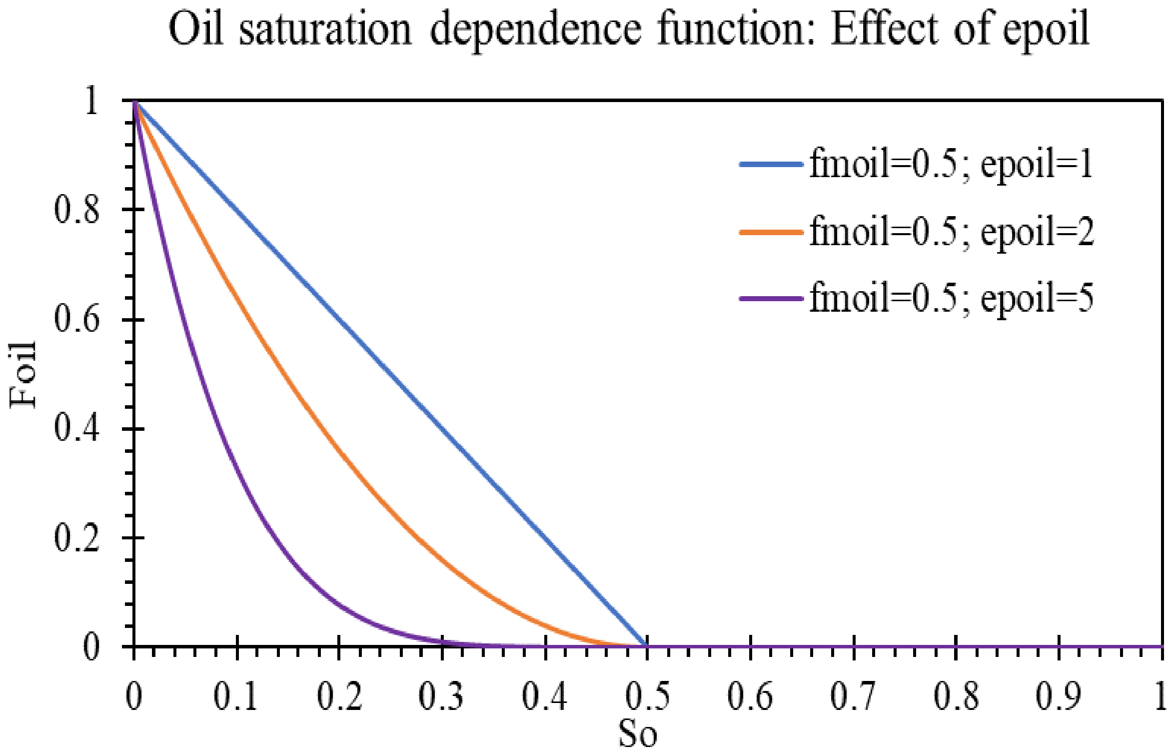
A CO_2 foam quality with 1 wt% TTM scan without oil and with 3% crude oil present, in an Indiana limestone core

Parameters in oil saturation dependent function: *fmoil & epoil*

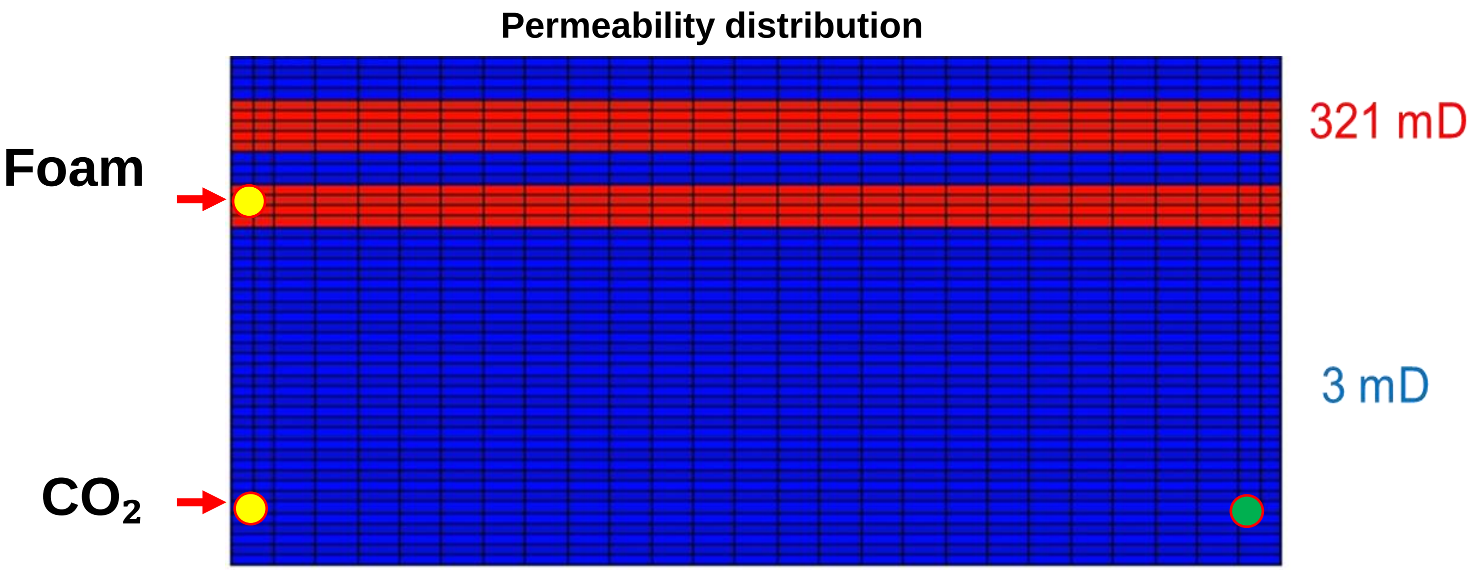




Oil saturation	Foil= $\begin{cases} \mathbf{0} \\ \left(\frac{fmoil - S_o}{fmsurf - floil}\right)^{epoil} \\ \mathbf{1} \end{cases}$	for $S_o > fmoil$ for $floil < S_o < fmoil$ for $S_o < floil$

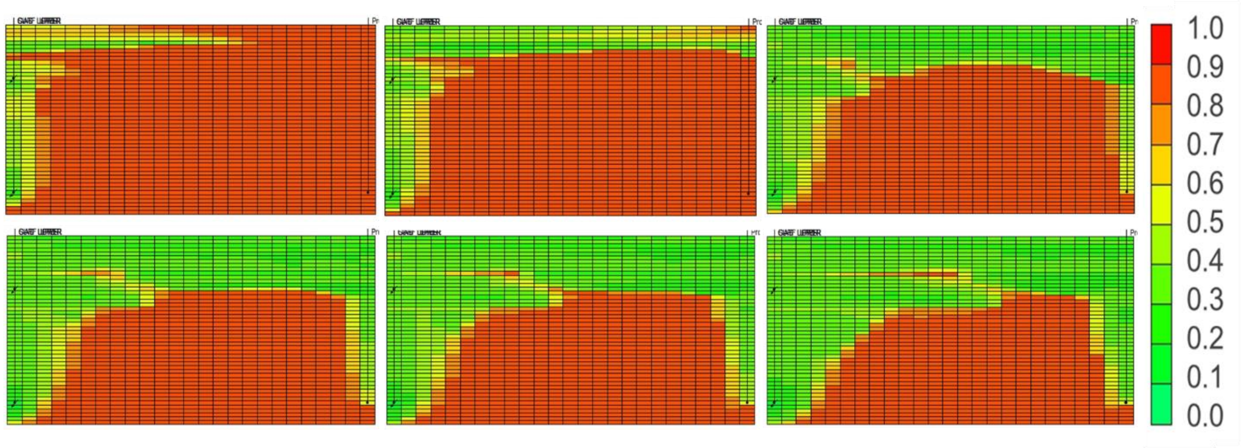
Heterogeneous reservoir model

Foam simulation at reservoir scale



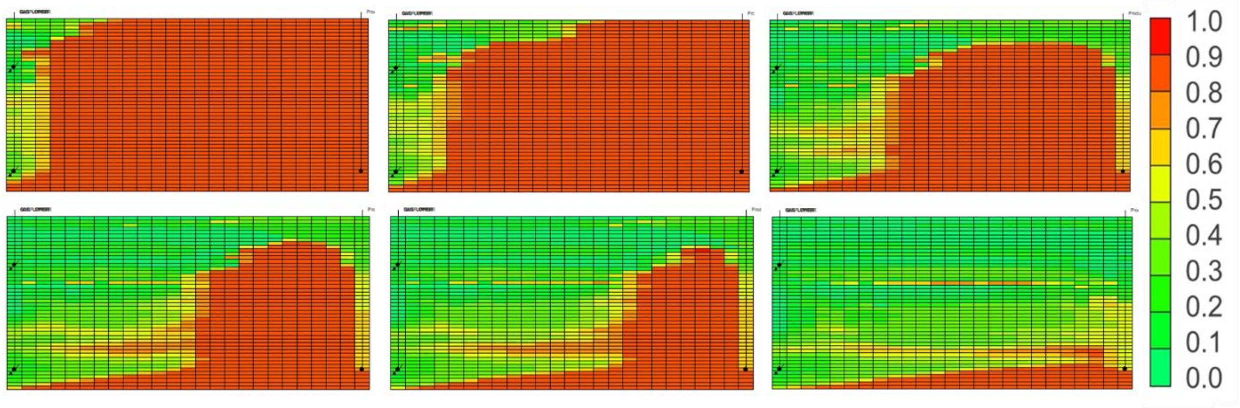
- A heterogeneous model reservoir is used
- Top layer permeability 321 mD
- Bottom layer permeability 3 mD
- STARS parameters from TTM foam test in a 321mD Indianan limestone
- Injected foam quality fg=0.8

Foam simulation at reservoir scale



No foam

Saturation of oil in the 1st, 2nd, 5th, 8th, 10th, and 15th years with coinjection of brine and CO_2 (80% quality)

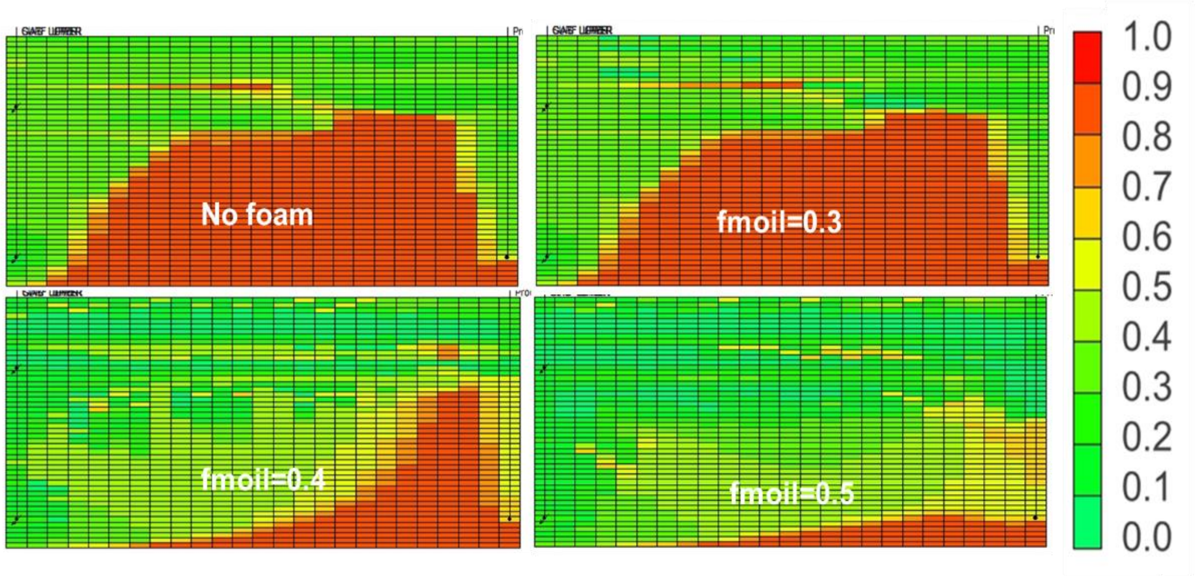


TTM Foam

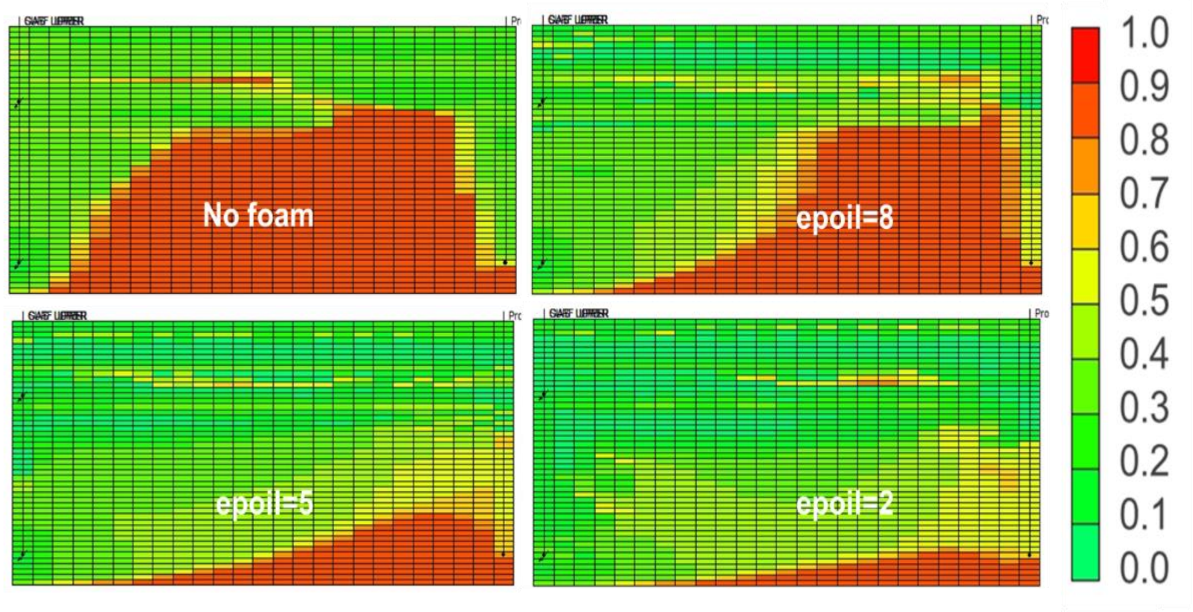
Saturation of oil in the 1st, 2nd, 5th, 8th, 10th, and 15th years with coinjection of TTM and CO_2 (80% quality)

$\boldsymbol{fmoil}$**=0.5,** $\boldsymbol{epoil}$**=1**

Effect of oil saturation parameters on foam



Effect of $fmoil$ on oil saturation after ~15 yrs of foam flooding at fixed $epoil$=1



Effect of $epoil$ on oil saturation after ~15 yrs of foam flooding at fixed $fmoil$=0.5

Conclusions

- **TTM is stable at high temperature and salinity**
- **Adsorption of TTM on carbonates is low provided that silica and clay contents are low**
- **In the absence of crude oil, TTM does not show MPG for foam generation**
- **TTM foam parameters were obtained, and reservoir simulation shows good mobility control results**
- **Oil saturation parameter plays an important role in the final enhanced oil recovery performance, large $epoil$ and small $fmoil$ will reduce the efficiency for TTM foam**

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References

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