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Enhanced Oil Recovery

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Impact of Rheology on Oil Recovery by Polymer Flooding, Analysed by Core Floods and Network Models

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Studies of fluids and interfaces in porous media

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Motivation

As you may know, polymers, in particular HPAM, are being applied in a number of fields around the world

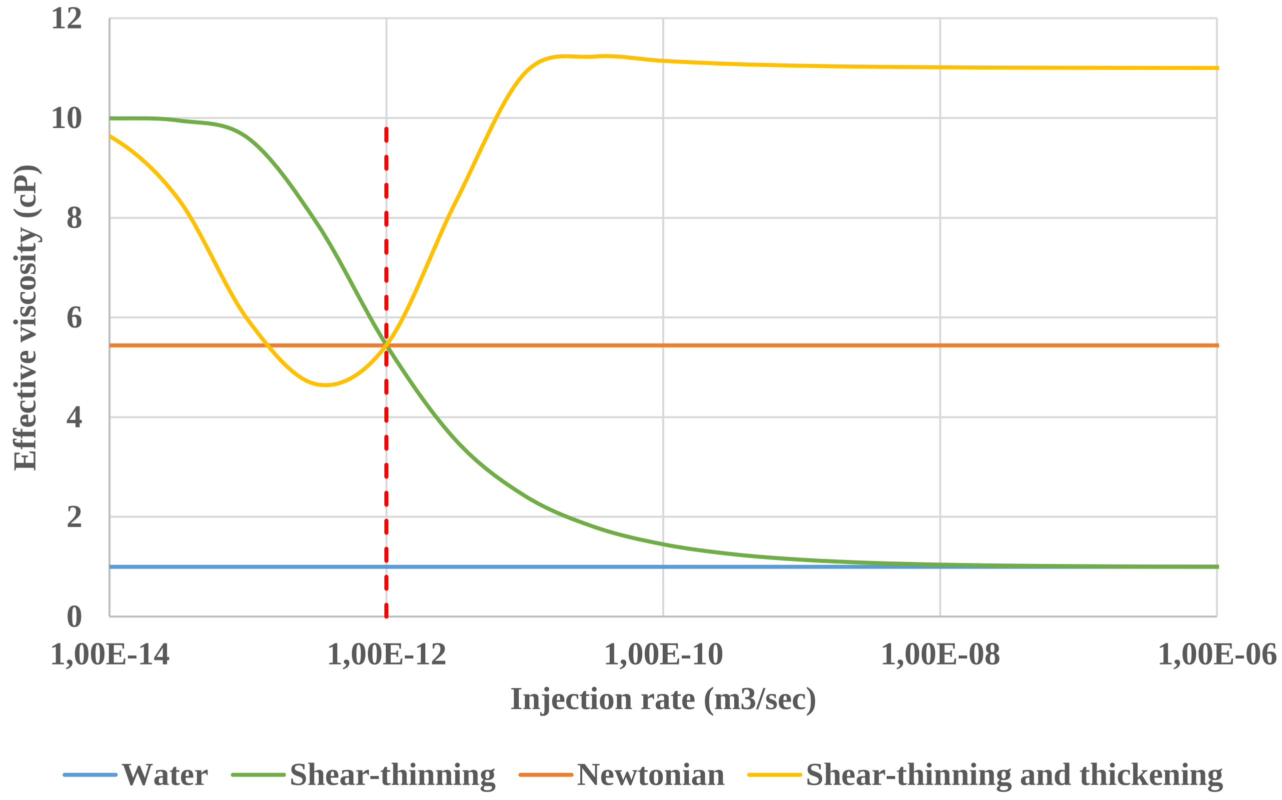
It is of key importance to understand the effect of polymer rheology on multiphase flow in porous media.

Recent heavy oil displacement experiments have shown that there are clear differences in incremental oil recovery for different polymers.

OBSERVATIONS: Significant higher recovery with HPAM compared to Xanthan and Newtonian fluids at same effective viscosity.

WHY?

Pore Network Single Phase Rheology



Three different polymer types are considered:

(i) Shear-thinning (Xanthan)
(ii) Newtonian
(iii) Shear-thinning and thickening (HPAM)

Outline

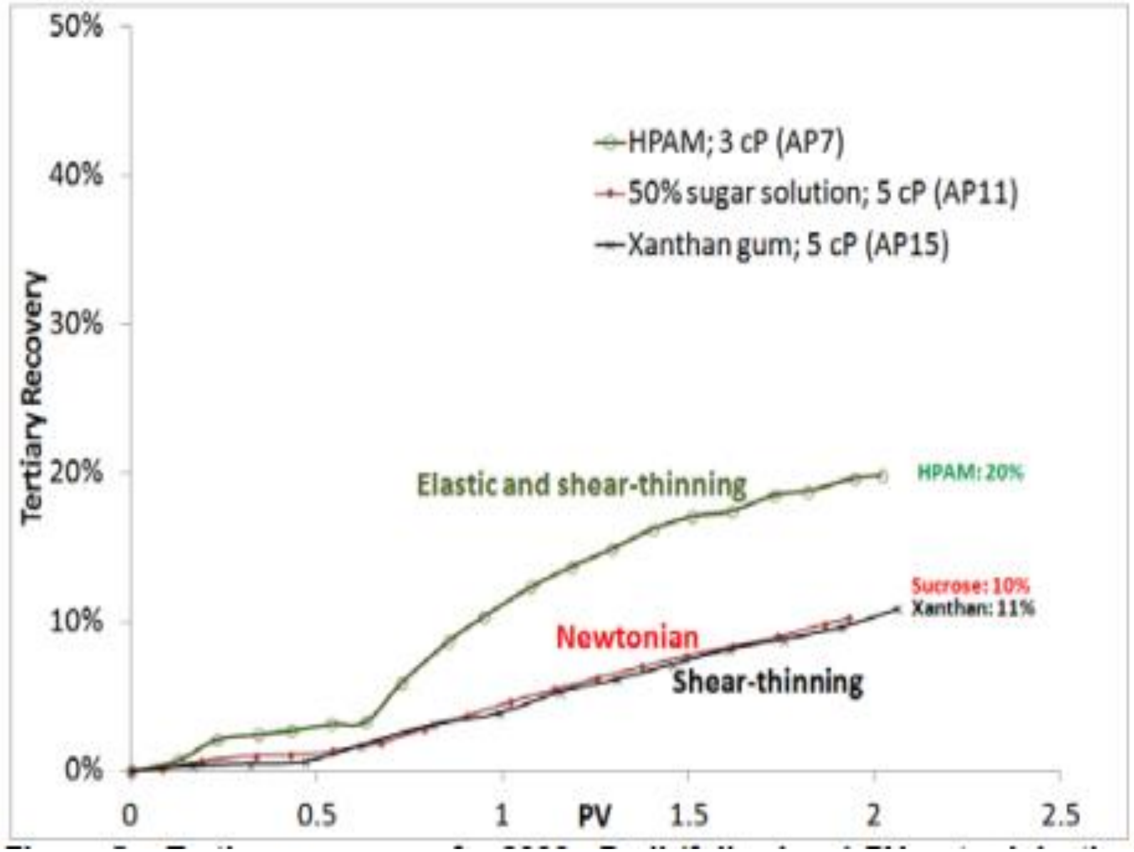
- Motivation
- Experimental results comparing HPAM to Xanthan and Newtonian fluids
  - **SPE165267** (2013) *Polymer Flooding of Heavy Oil Under Adverse Mobility Conditions*: Levitt, Jouenne, Bondino, Santanach-Carreras, Bourrel.
  - **SPE190866** (2018) *Viscous Oil Recovery by Polymer Injection; Impact of In-Situ Polymer Rheology on Water Front Stabilization*: Vik, Kedir, Kippe, Sandengen, Skauge, Solbakken, Zhu.
- Dynamic pore scale model
- Dynamic pore scale modeling results
- Summary and Conclusion

Experimental Results

SPE165267 (2013) *Polymer Flooding of Heavy Oil Under Adverse Mobility Conditions*: Levitt, Jouenne, Bondino, Santanach-Carreras, Bourrel (TOTAL)

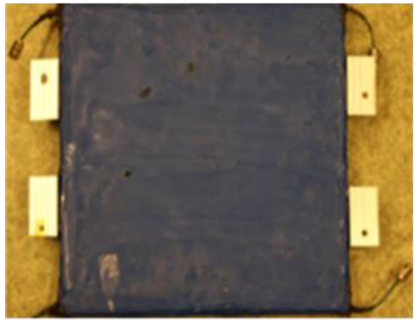
- Bentheimer Lab Core
- Tertiary Polymer Flood:
  - Xanthan injection: SHEAR-THINNING
  - Sucrose injection: NEWTONIAN
  - HPAM injection: SHEAR-THINNING and THICKENING
- Permeability: ~ 2000 mD
- Oil viscosity: ~ 2000 cP
- Similar polymer viscosity

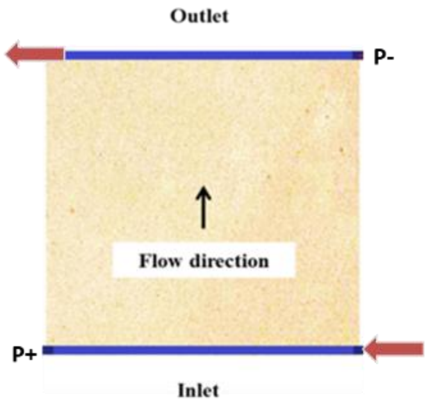
Why is HPAM giving much higher extra oil recovery?



Experimental Results

SPE190866 (2018) *Viscous Oil Recovery by Polymer Injection; Impact of In-Situ Polymer Rheology on Water Front Stabilization*: Vik, Kedir, Kippe, Sandengen, Skauge, Solbakken, Zhu.





- Bentheimer Slab
- Secondary Polymer Flood:
  - Water injection: NEWTONIAN
  - Xanthan injection: SHEAR-THINNING
  - Glycerol injection: NEWTONIAN (viscous water)
  - HPAM injection: SHEAR-THINNING and THICKENING

- Permeability: ~ 2000 mD
- Oil viscosity: ~ 466 cP
- Injection rate, Q = 0.05 and 0.3 ml/min

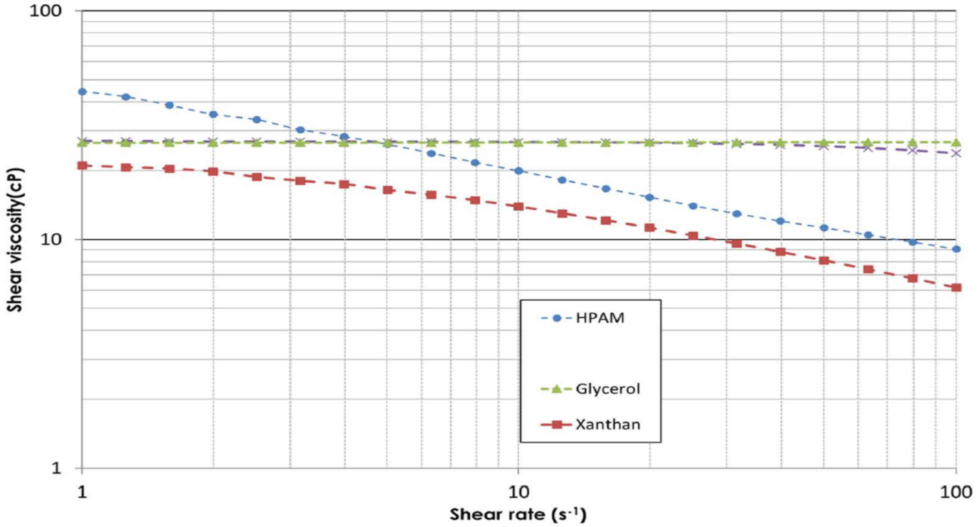
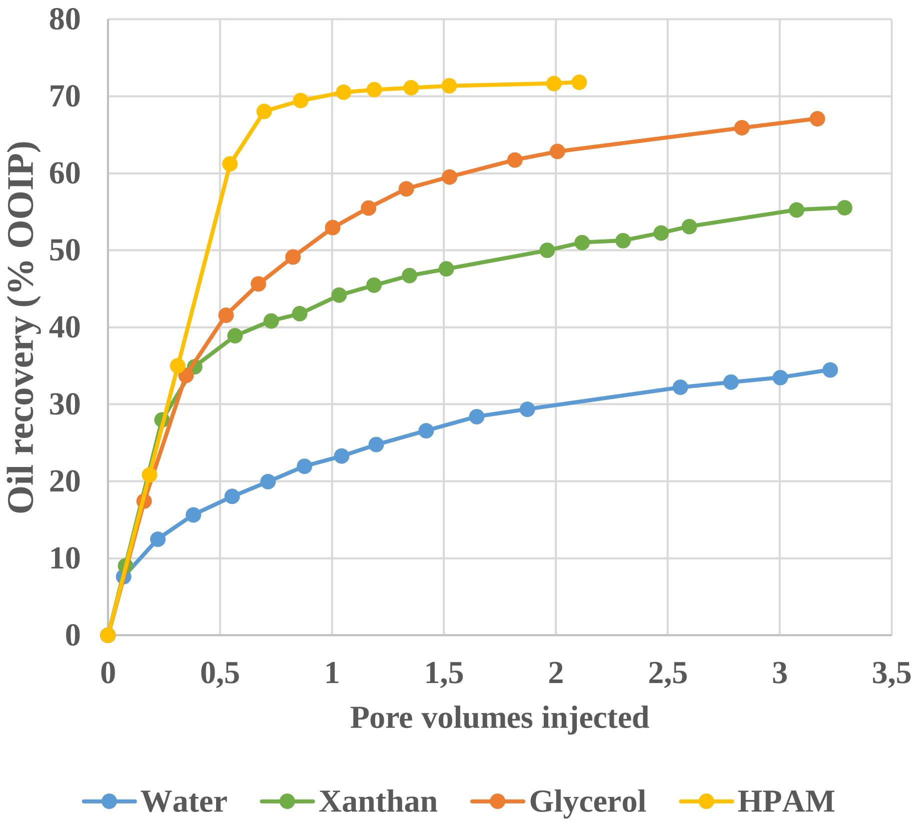


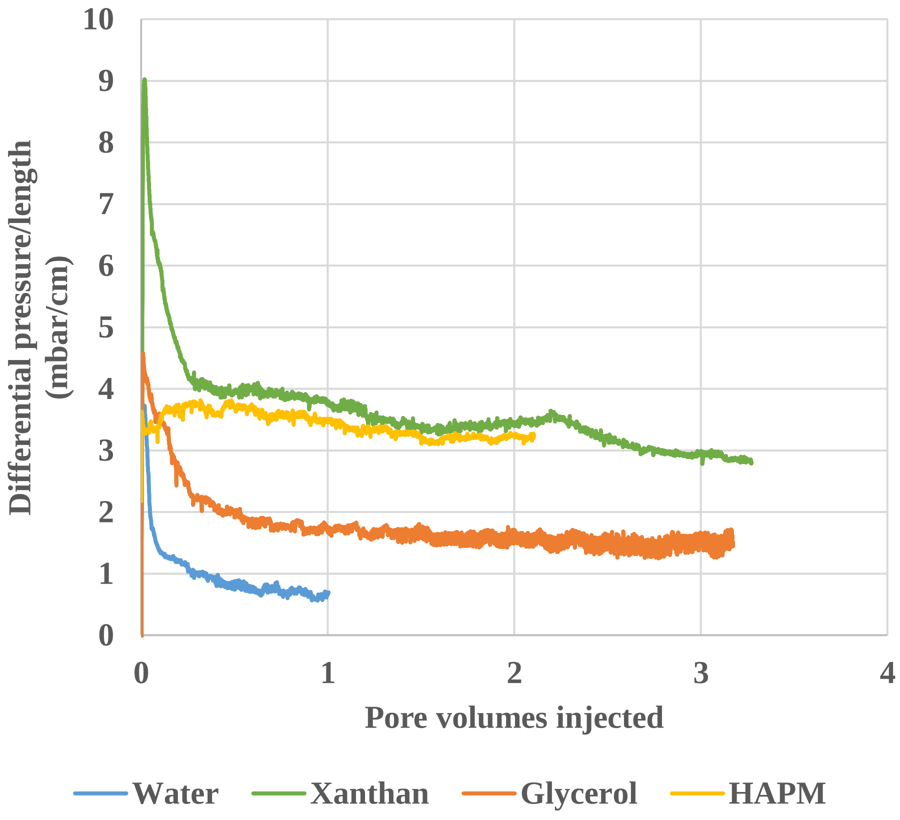
Figure 3—Bulk rheology for solutions used and compared in the slab floods. The shear degraded HPAM-S solution matches the glycerol up to 40s^{-1} matches

Experimental Results

SPE190866 (2018) *Viscous Oil Recovery by Polymer Injection; Impact of In-Situ Polymer Rheology on Water Front Stabilization*: Vik, Kedir, Kippe, Sandengen, Skauge, Solbakken, Zhu.

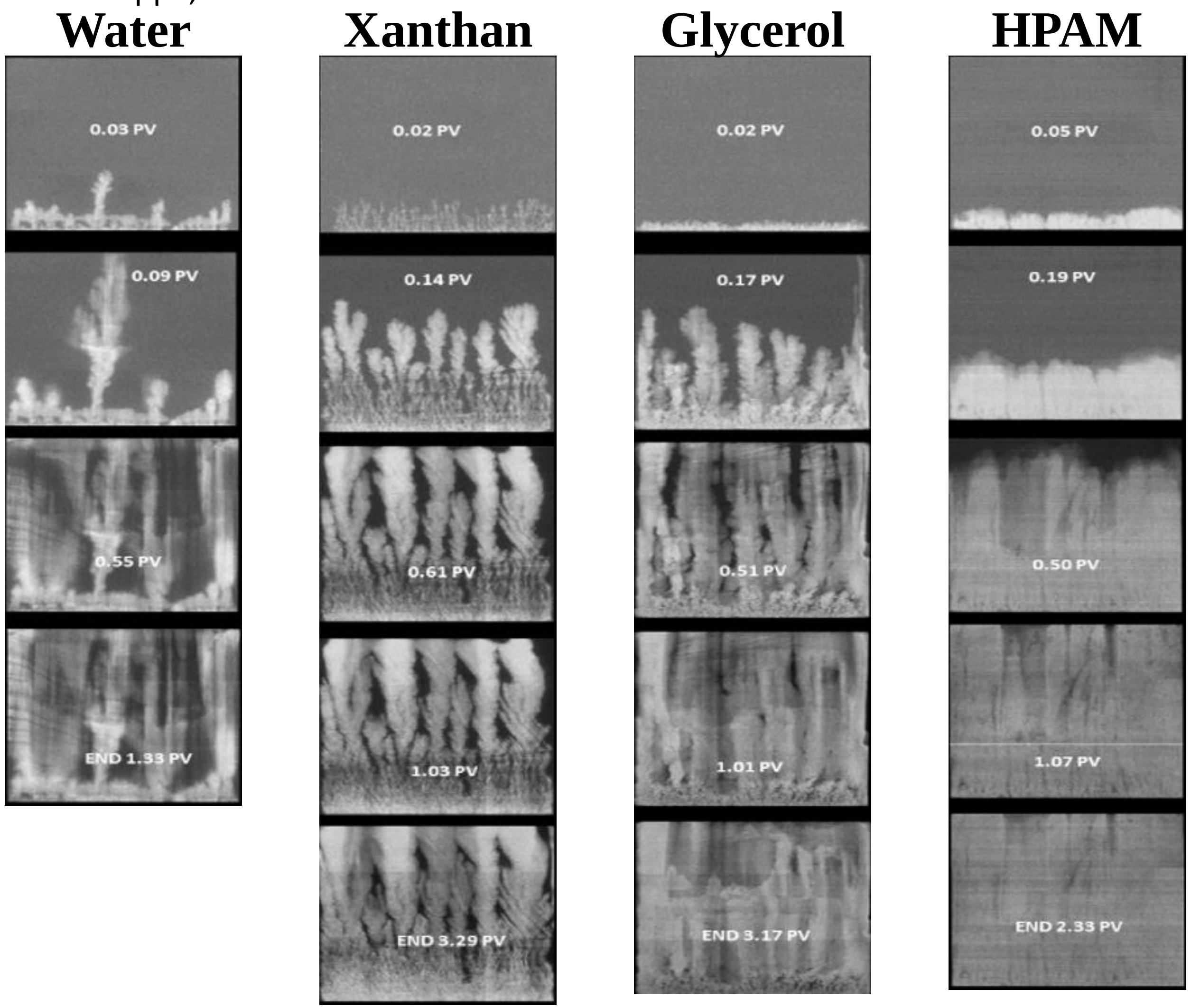
- Large difference in oil mobilization depending on rheology



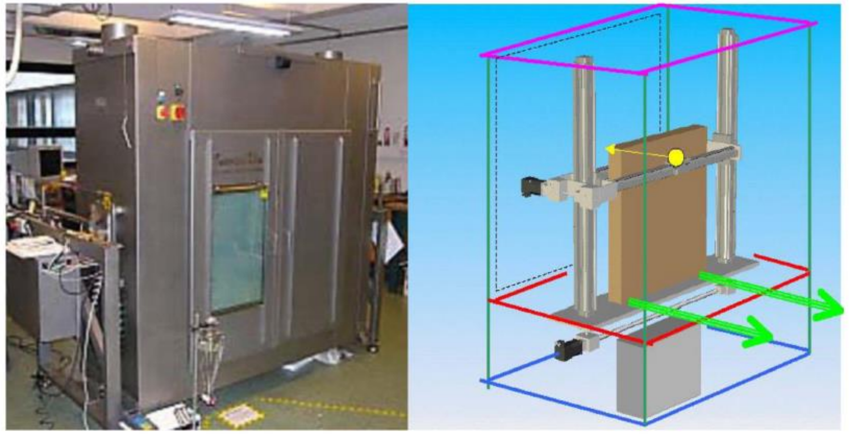


Experimental Fluid Distribution

SPE190866 (2018) *Viscous Oil Recovery by Polymer Injection; Impact of In-Situ Polymer Rheology on Water Front Stabilization*: Vik, B., Kedir, A., Kippe, V. et *al*.



- Unstable displacement
- X-ray images reveal mechanism
- Rheology changes amount of and distribution of by-passed oil



Results show better sweep with HPAM

Dynamic 2-phase Pore Network Model

Dynamic ***imbibition*** model based on work by
Li et al. (2017) and extended to include EOR processes, especially polymer flooding
(Zamani, Salmo, Sorbie, Skauge (2019))

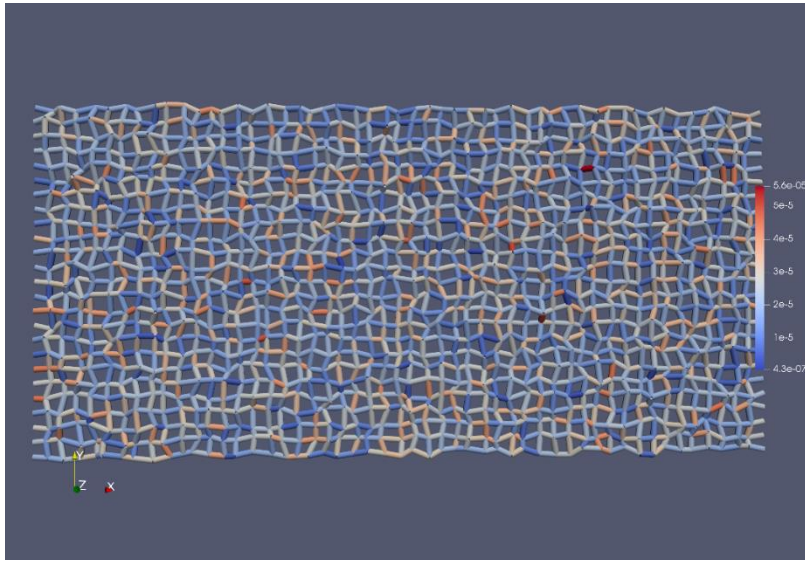
Dynamic = non steady state modelling of IMBIBITION

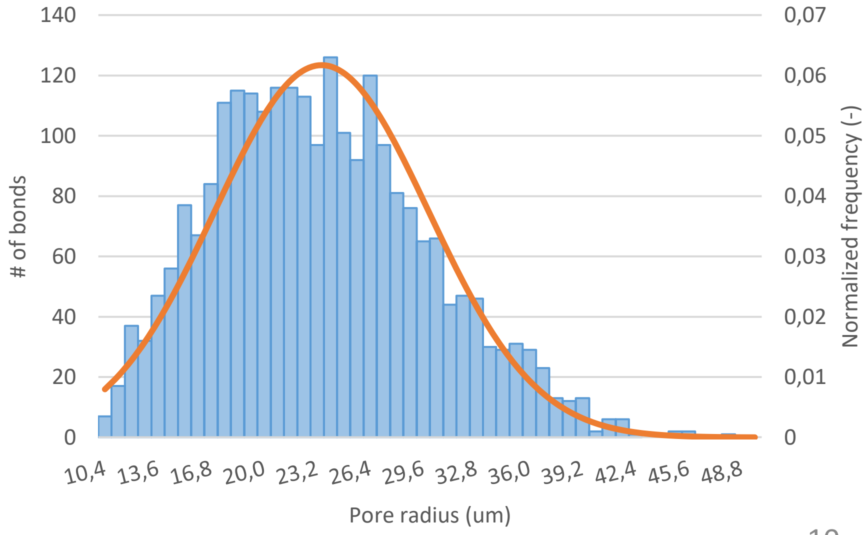
Includes both piston-like and film flow/snap-off pore scale processes

BOTH viscous and capillary forces

➔ Important since must change the balance of viscous/capillary forces and hence ….

➔ Have the capability for microscopic diversion to emerge (if it happens)





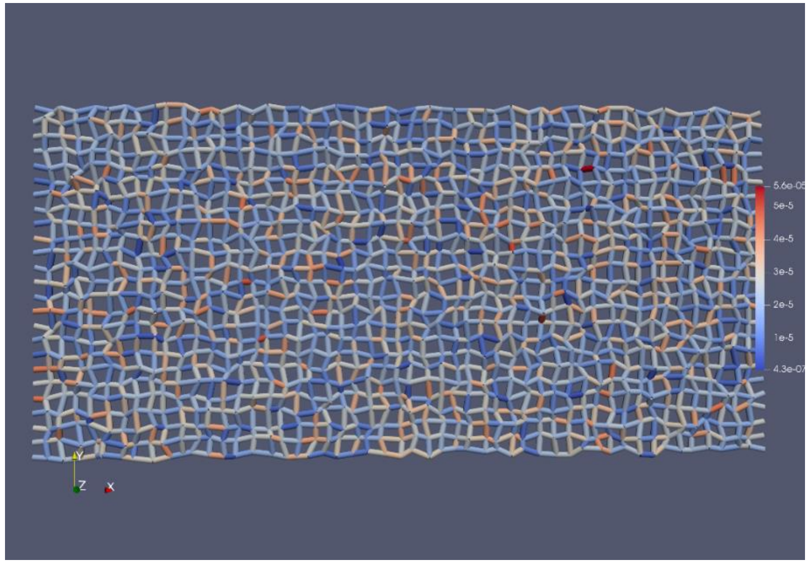
Li, J., McDougall, S. R., Sorbie, K. S. (2017). *Dynamic pore-scale network model (PNM) of water imbibition in porous media*. Advances in Water Resources.
Zamani, Salmo, Sorbie, Skauge. *Numerical Study of Polymer Flow in Porous Media using Dynamic Pore Network Modelling*.

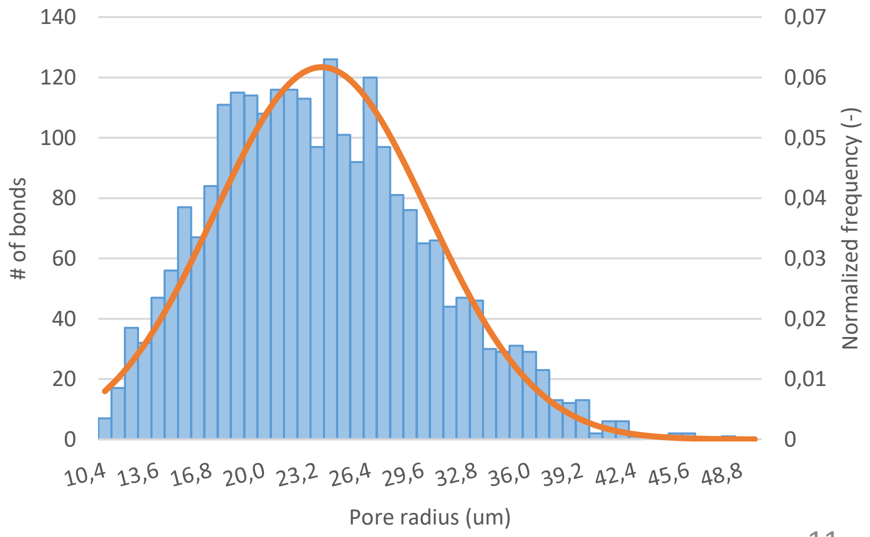
Dynamic 2-phase Pore Network Model

Based on single pore event of filling bonds in the pore network

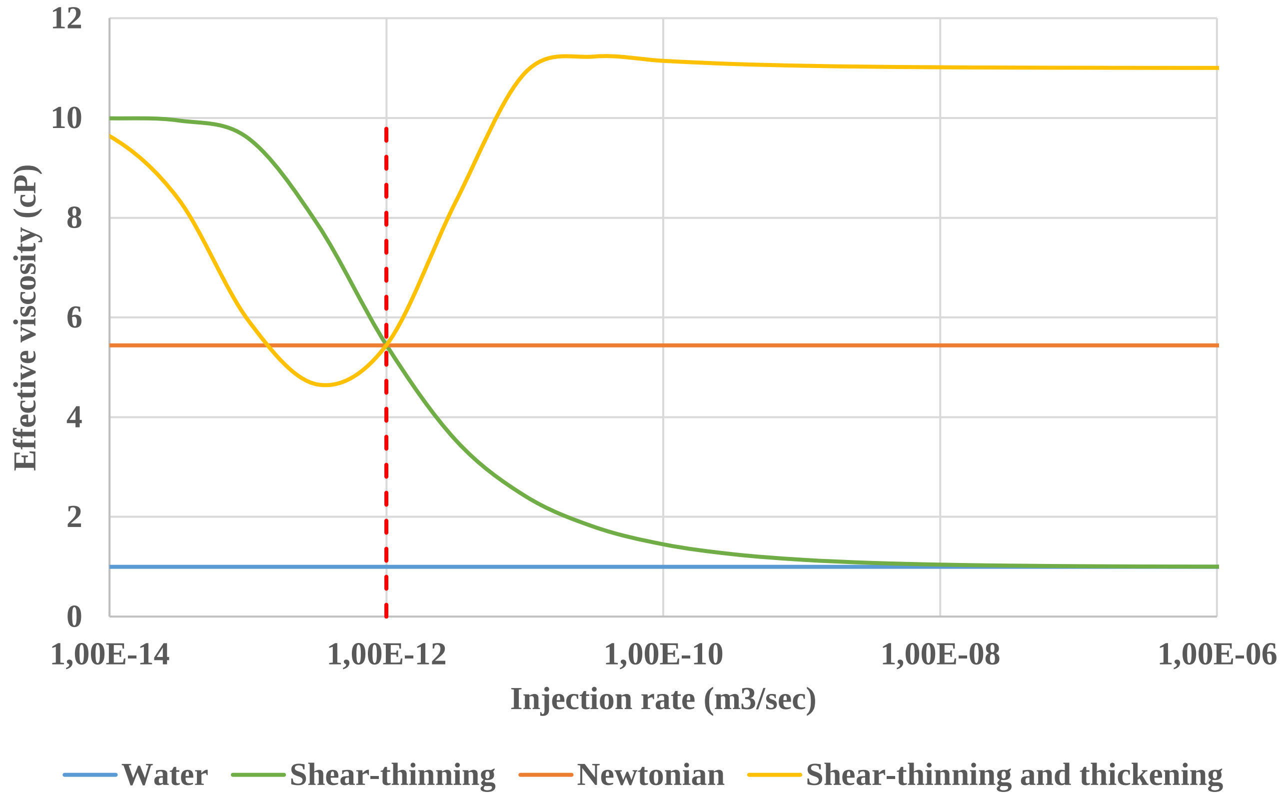
Simulation can give insight into matters such as finger density (number of fingers)

Parameter	Unit	Value
Network size	-	50 × 25 × 1
Coordination number	-	4
Pore size distribution model	µm	$\bar{r}$ = 18, σ = 9
Minimum inscribed radius	µm	10
Maximum inscribed radius	µm	50
Permeability	mD	2069
Distortion factor	-	0.3
Average pore length	µm	333
Pore half angles	-	30, 30, 30
Wettability	-	Water wet
Water/oil contact angle	Degree	0
Interfacial tension	N/m	0.0004
S_{wi}	-	0
Injection rate	m^3/sec	1e-12
Capillary No. (waterflood)	-	3.28e-6
Oil viscosity	cP	466





Pore Network Single Phase Rheology



Three different polymer types are considered:

(i) Shear-thinning

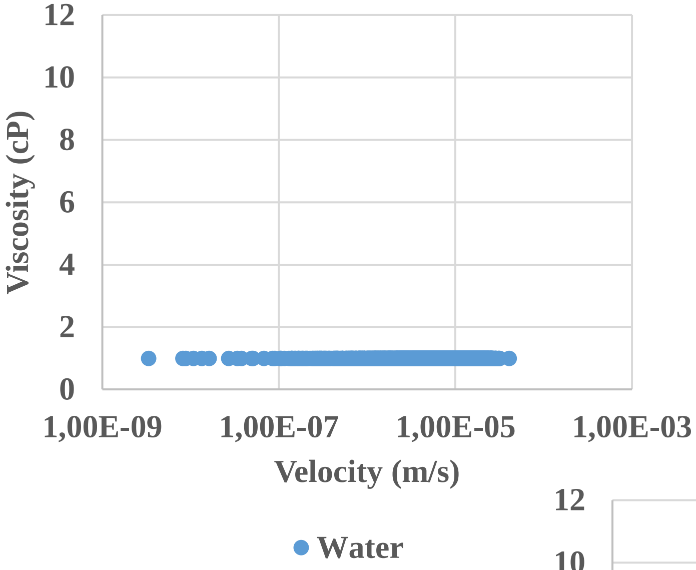
(ii) Newtonian

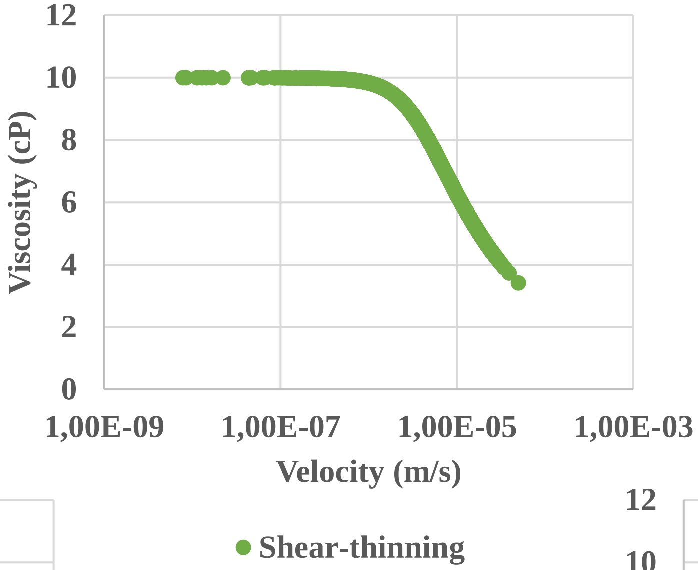
(iii) Shear-thinning and thickening

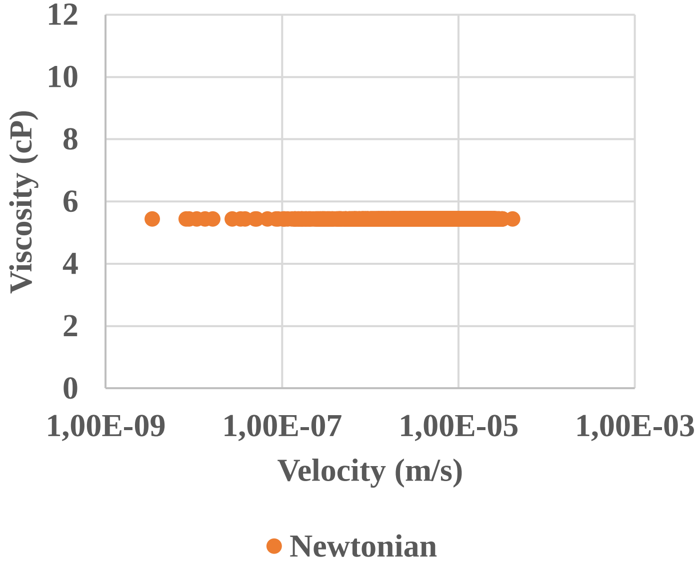
The apparent viscosity is calculated:

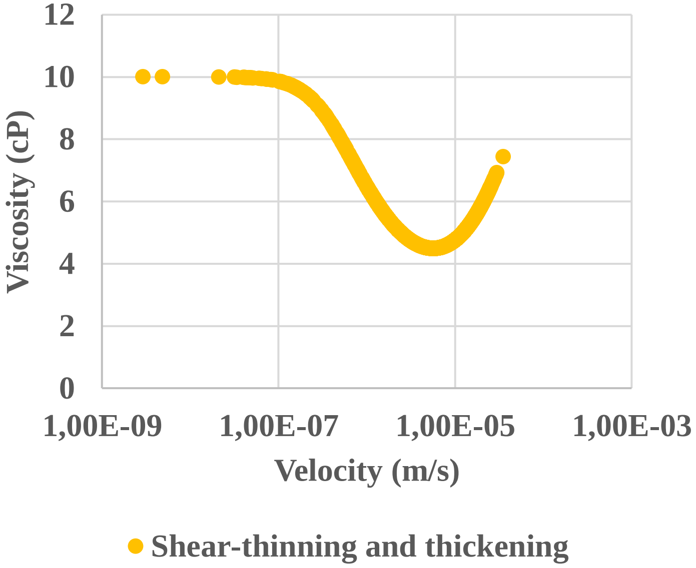
$$\mu_{app} = \frac{\Delta P_p}{\Delta P_w} \mu_w$$

Single Phase In-Situ Viscosity

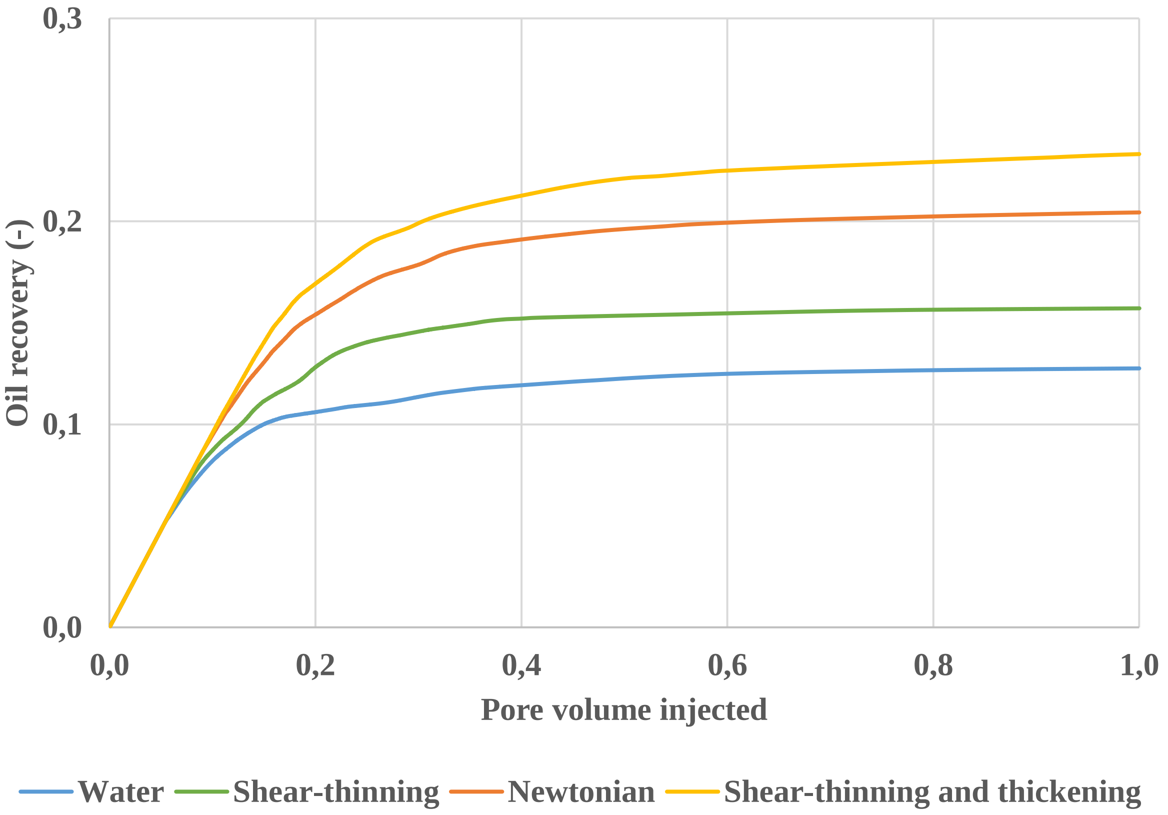


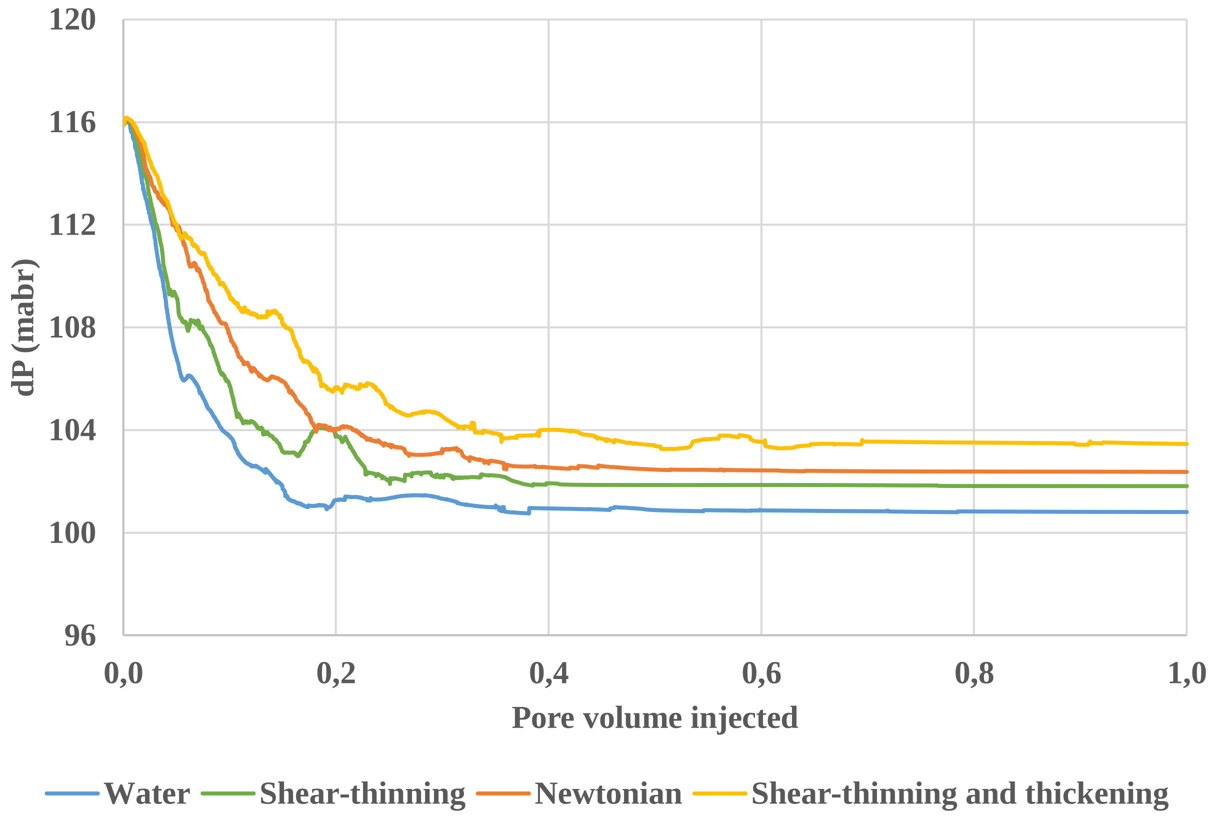




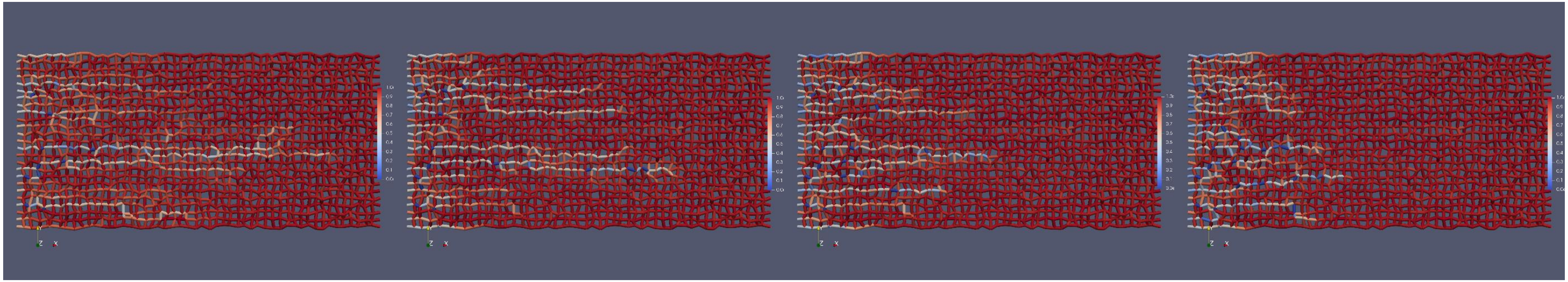


Oil Recovery and Pressure



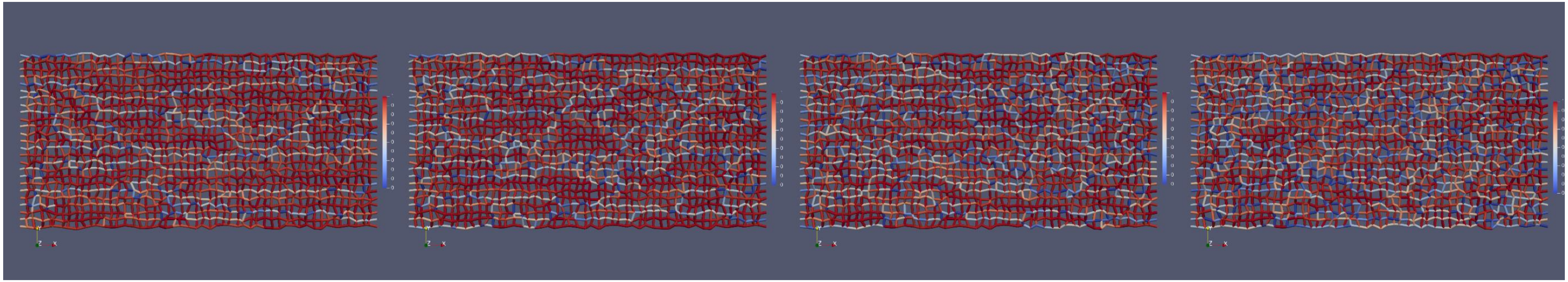


Fluid Distribution



Water **Xanthan** **Glycerol** **HPAM**

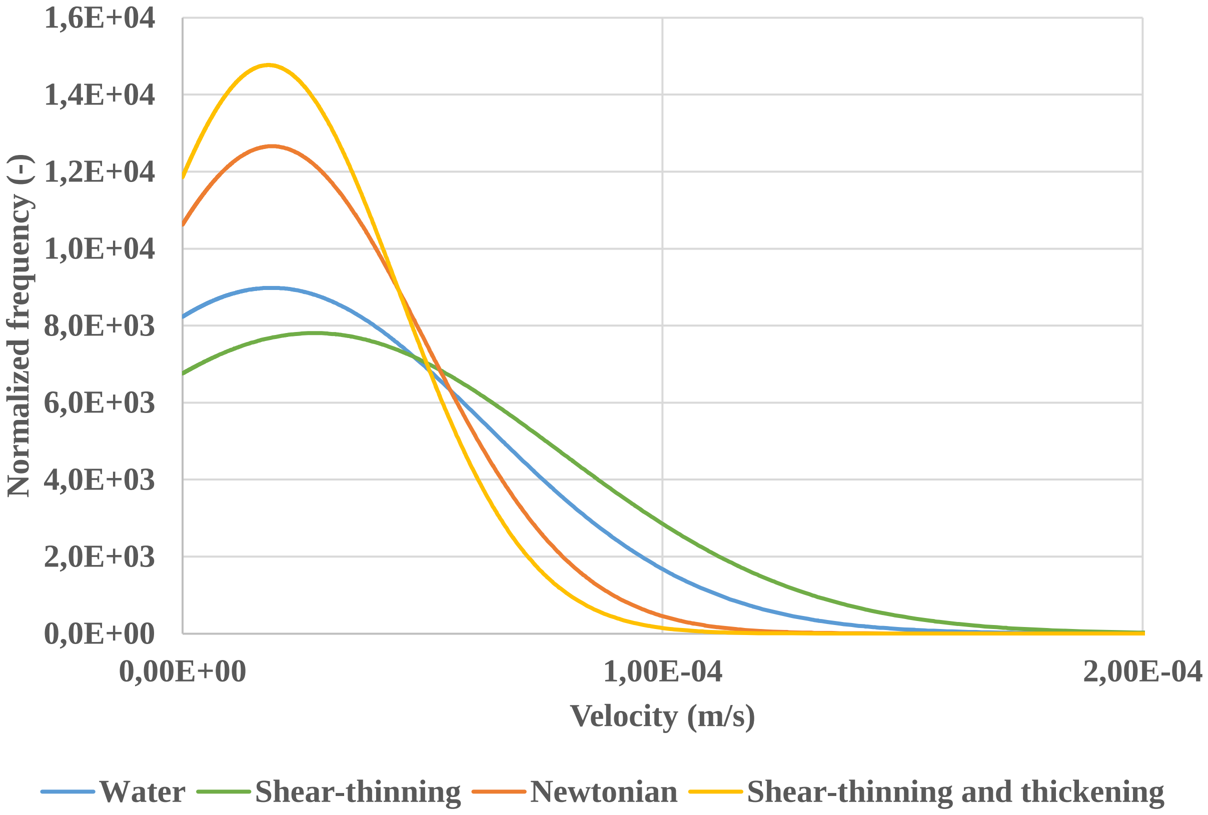
Fluid distribution (oil and water) after 0.5 PV of injected fluid.

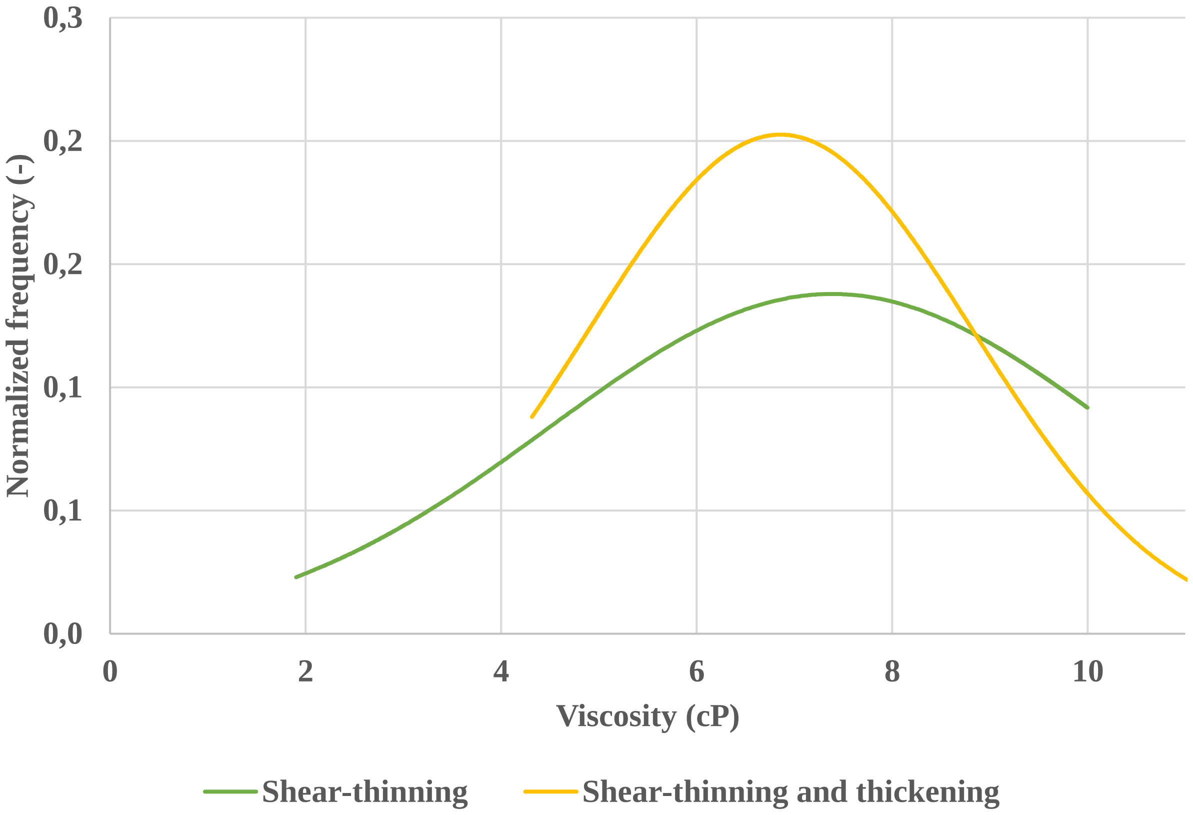


Water **Xanthan** **Glycerol** **HPAM**

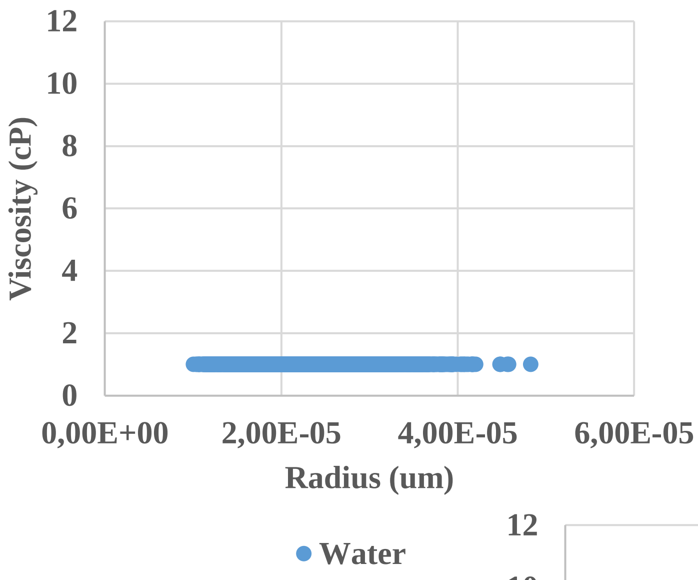
Fluid distribution (oil and water) after 1.0 PV of injected fluid.

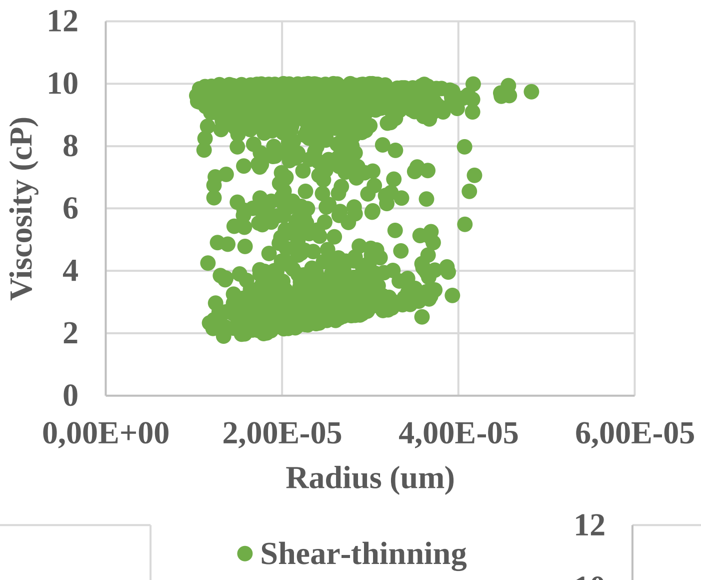
In-Situ Velocity and Viscosity

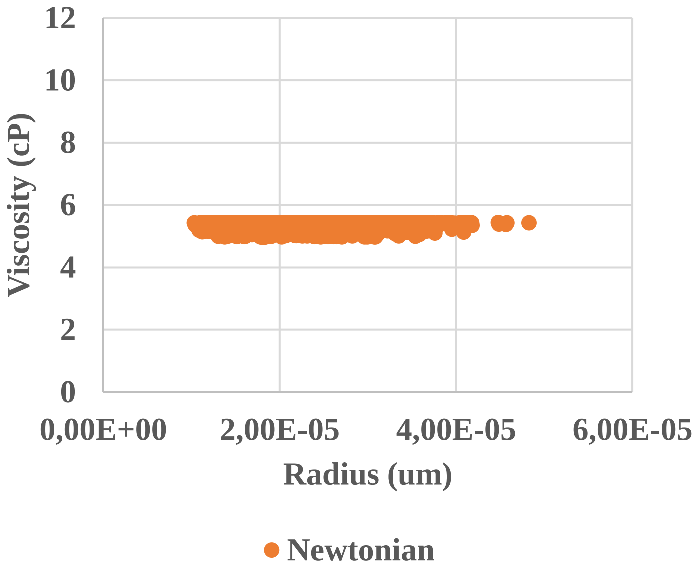


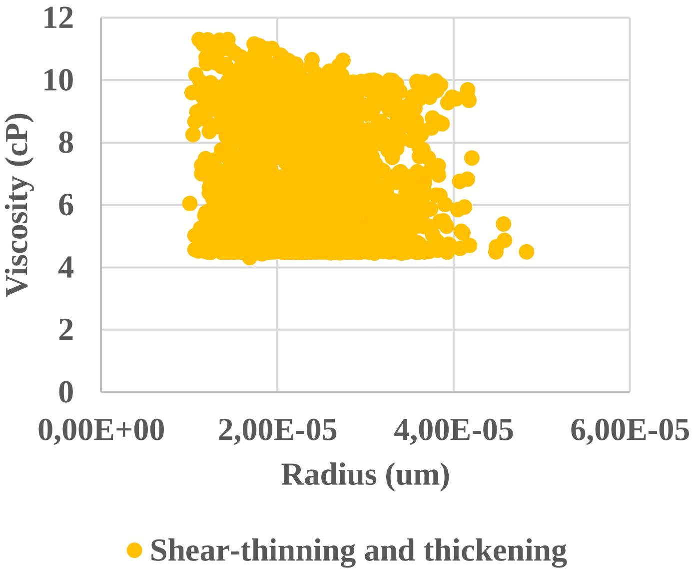


Two Phase In-Situ Viscosity vs. Radius

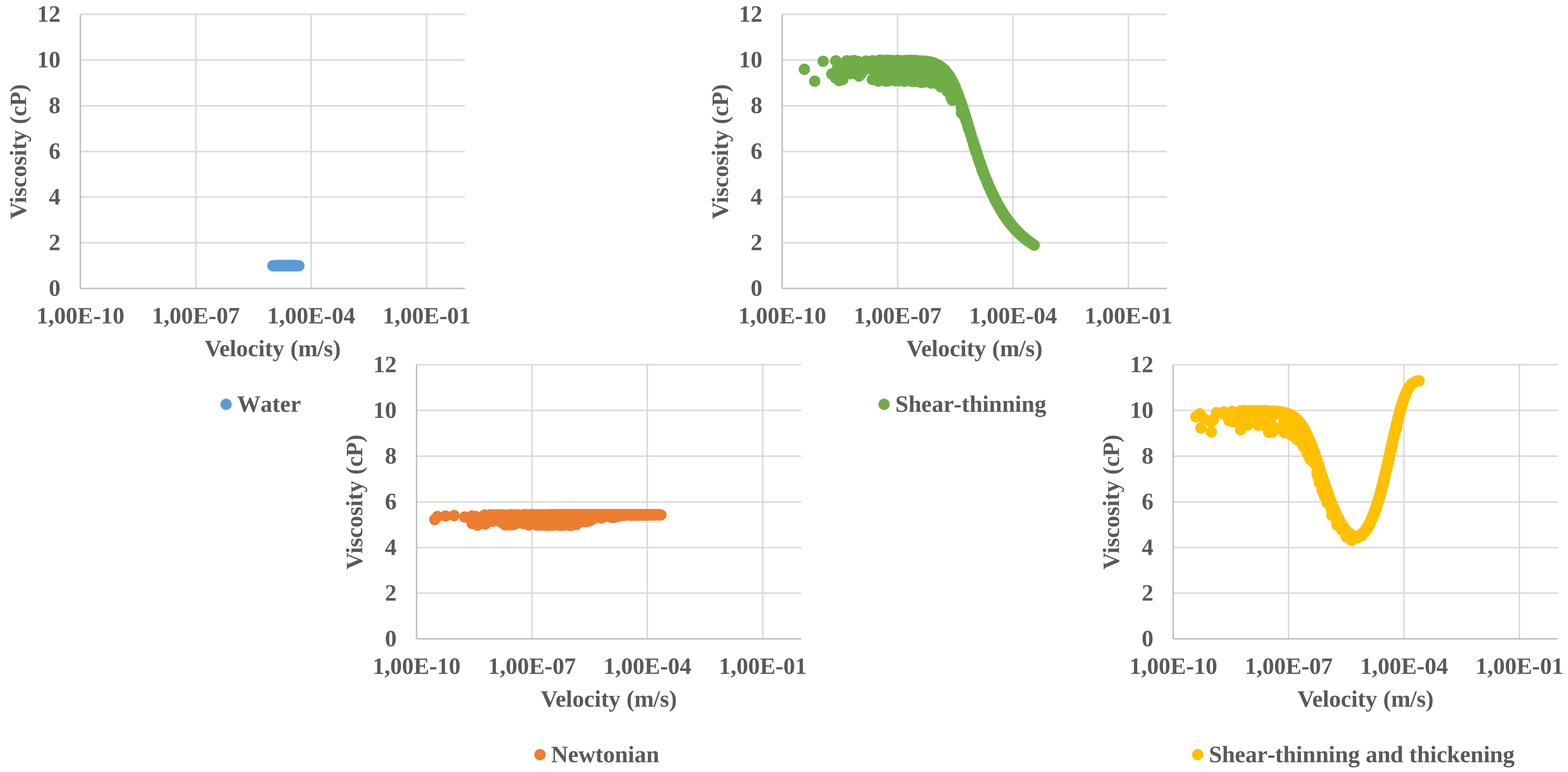




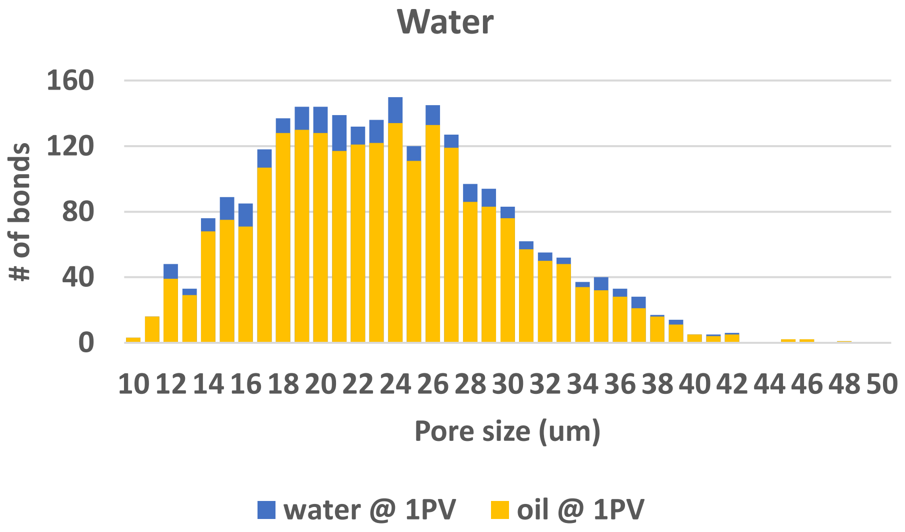


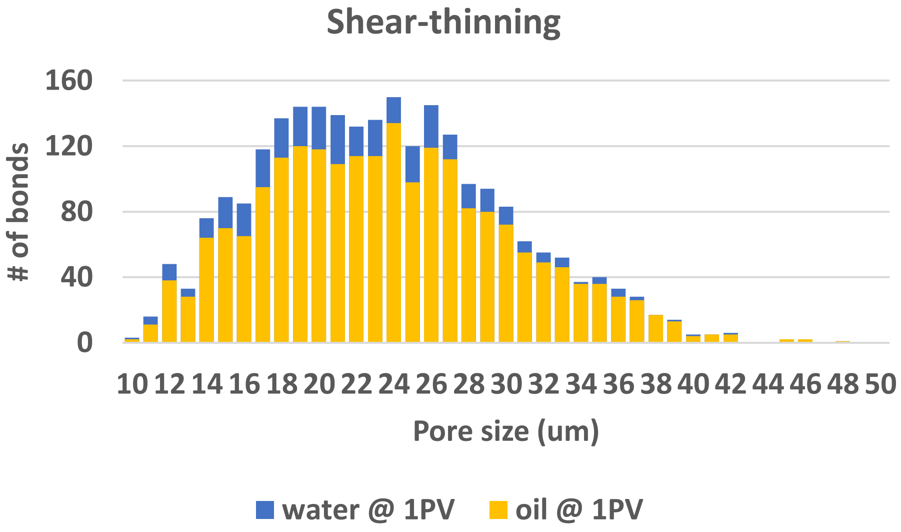


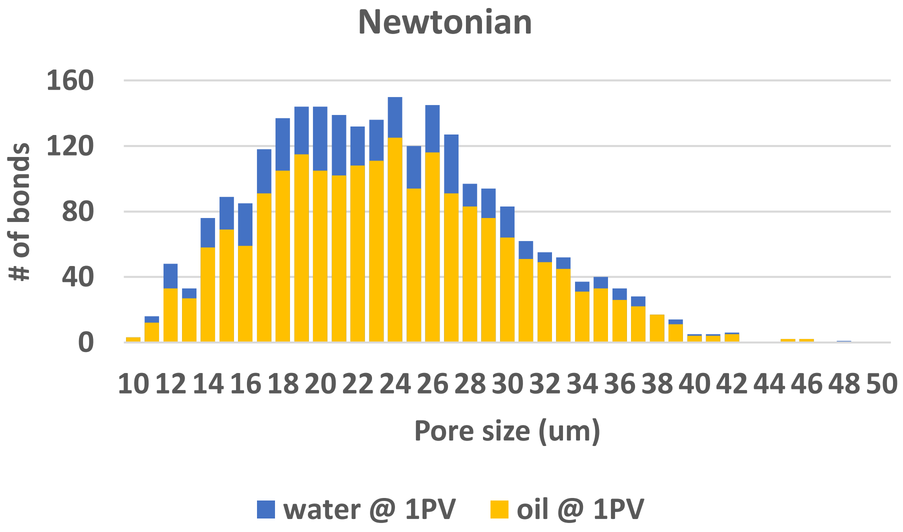
Two Phase In-Situ Viscosity vs. Velocity

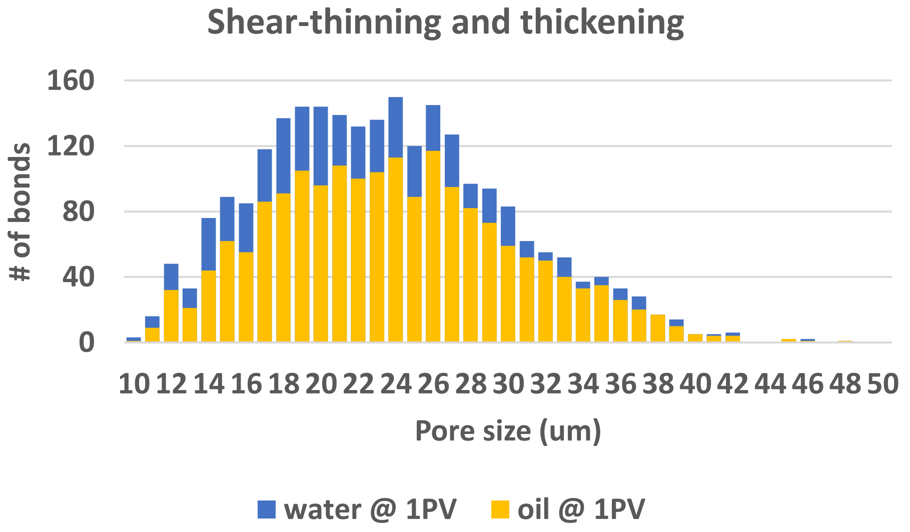


Pore Occupancy – 50% filling criteria

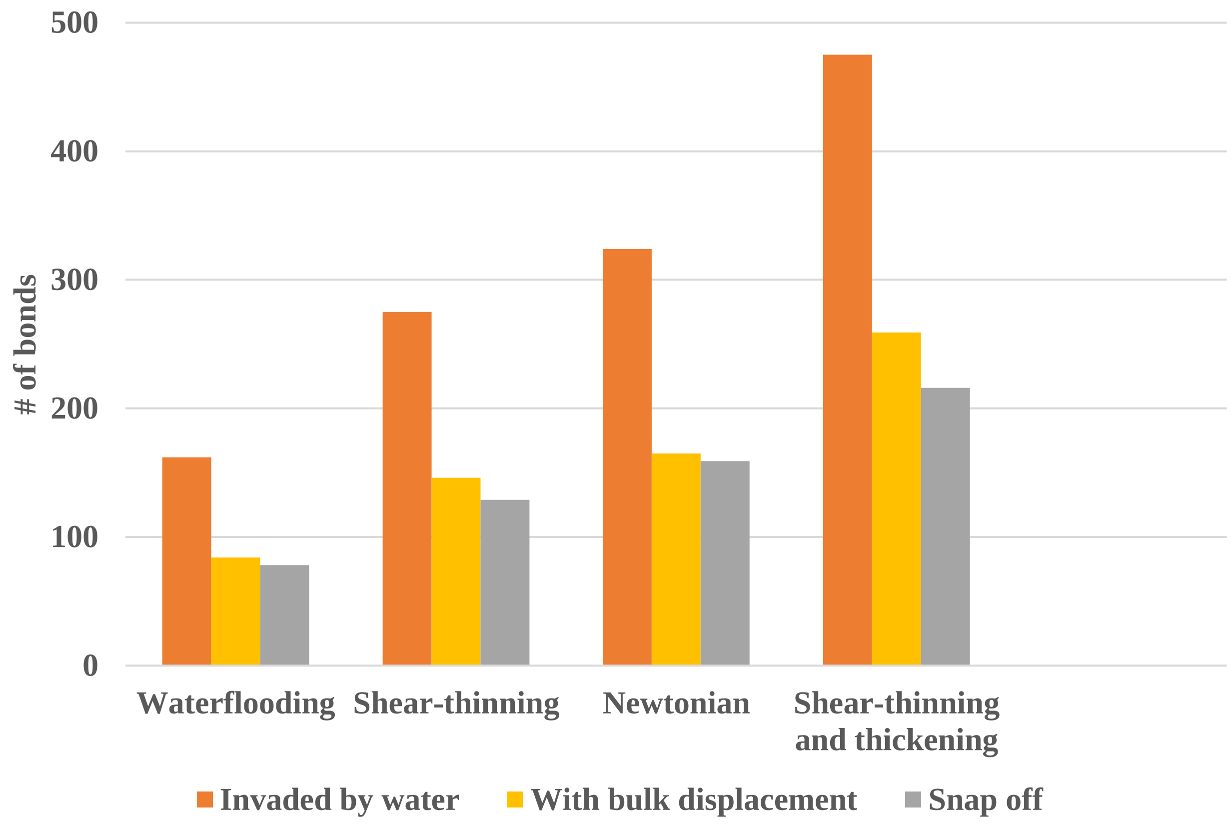




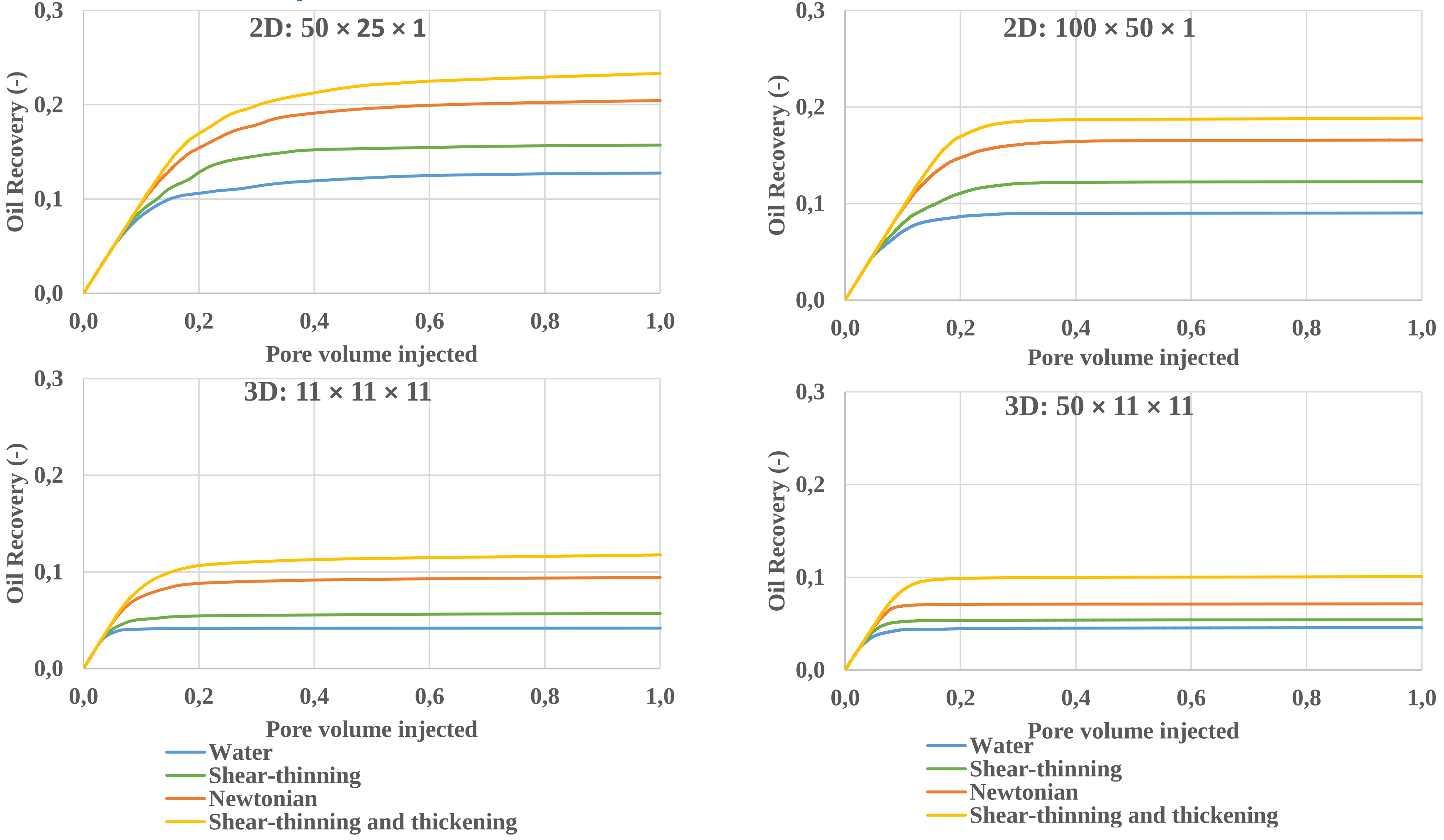




Bulk and Snap-Off Displacement



Oil Recovery Profiles for Different Model Sizes



Summary and Conclusions 1

- Polymer solution increase oil recovery compared to water flooding at adverse mobility.

- Combined shear-thinning and thickening polymer (HPAM like) improves the performance more than Newtonian (glycerol) and purely shear-thinning polymer (xanthan).

- This is in exact qualitative agreement with the correct experimental observations in order of oil recovery and that there were significant differences between all the cases.

Summary and Conclusions 2

- The pore network model shows that shear-thinning polymer experience higher flow velocity, thus lower viscosity which approaches water viscosity at higher flow rates. A more severe and inefficient finger pattern are observed for shear-thinning polymer (xanthan), compared to combined shear-thinning and thickening, which is very consistent with experimental observations.

- Examining the pore scale occupancies, it is evident that the best performing shear-thinning and thickening (HPAM like) case causes more injected phase fluid diversion at the local scale, displacing more oil from the intermediate sized pores.

Acknowledgment to JIP sponsors:

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