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MAERSK OIL

MEOR:
From an Experiment to a Model

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Stavanger, 18 Nov 2014

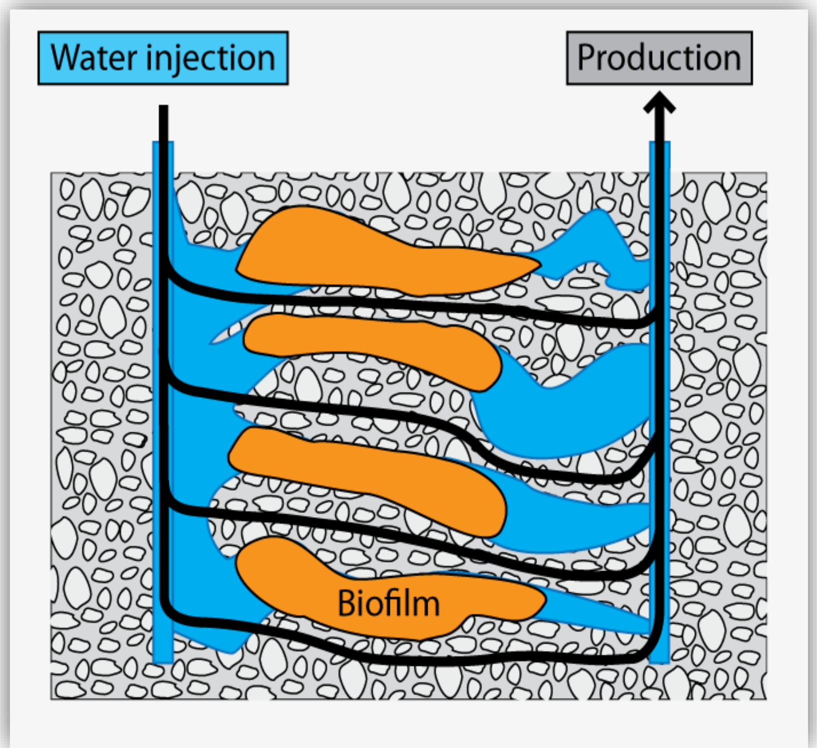
RECOVERY MECHANISMS

Reduction of oil-water interfacial tension (IFT) by surfactant production and bacteria.

Fluid diversion by microbial plugging.

Reduction of oil viscosity.

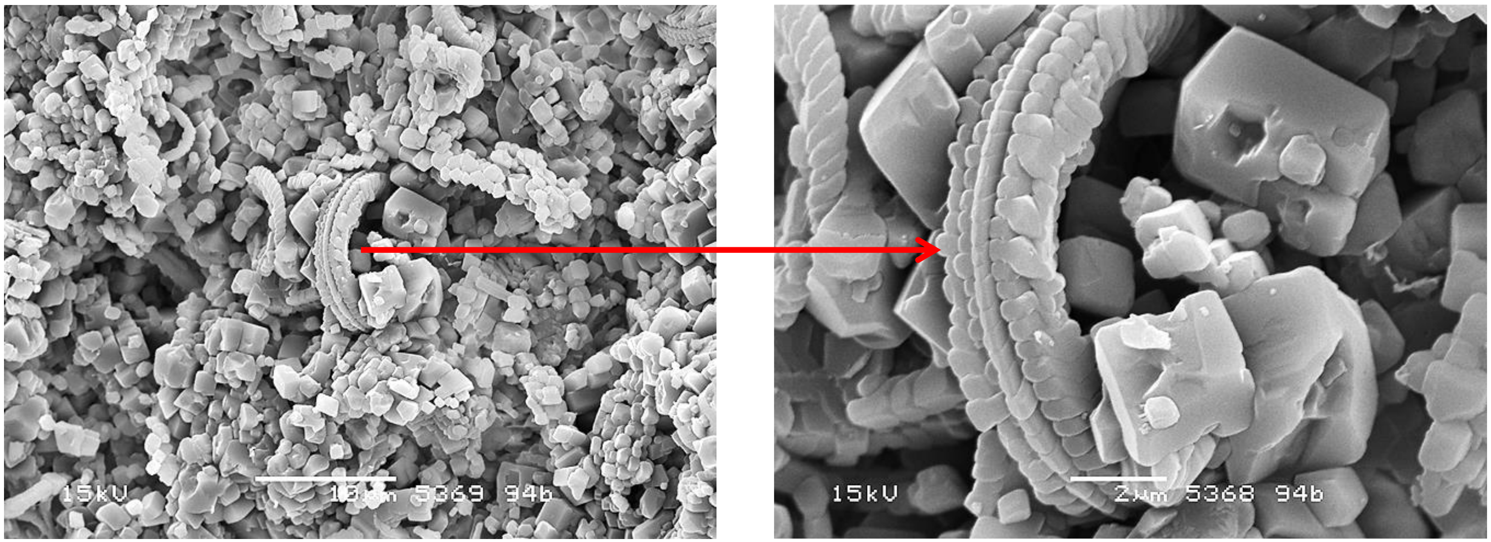
Gas production.



EXPERIMENTS

CHALK ROCK

North Sea Reservoirs are mainly chalk reservoirs



Scanning Electron Microscope of Cretaceous, Maastrictian M1b1 unit reservoir chalk (Maersk Oil, 2014)

Chalk rock: Small pore throats, comparable to microbe sizes

Stevns Klint outcrop: Model study, pore throat size: 0.004-6.1µm

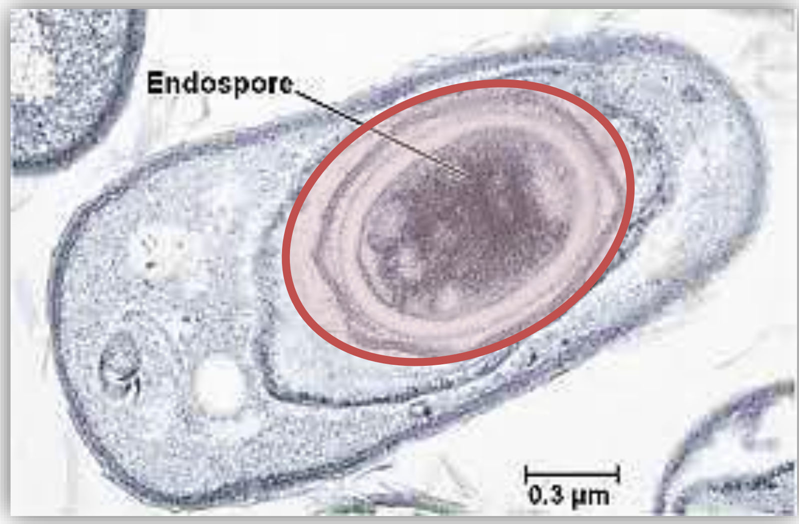
Bacterial sizes: 0.5x3µm

SPORE PROPERTIES

Model bacteria used in penetration test:

Bacillus licheniformis 421 (spore-forming)

Pseudomonas putida K12



http://bio1151.nicerweb.com/Locked/media/ch27/endospore.html

Vegetative cell

Growing with metabolism.

Spore

Sporulation induced by stress.

Dormant (non-growing).

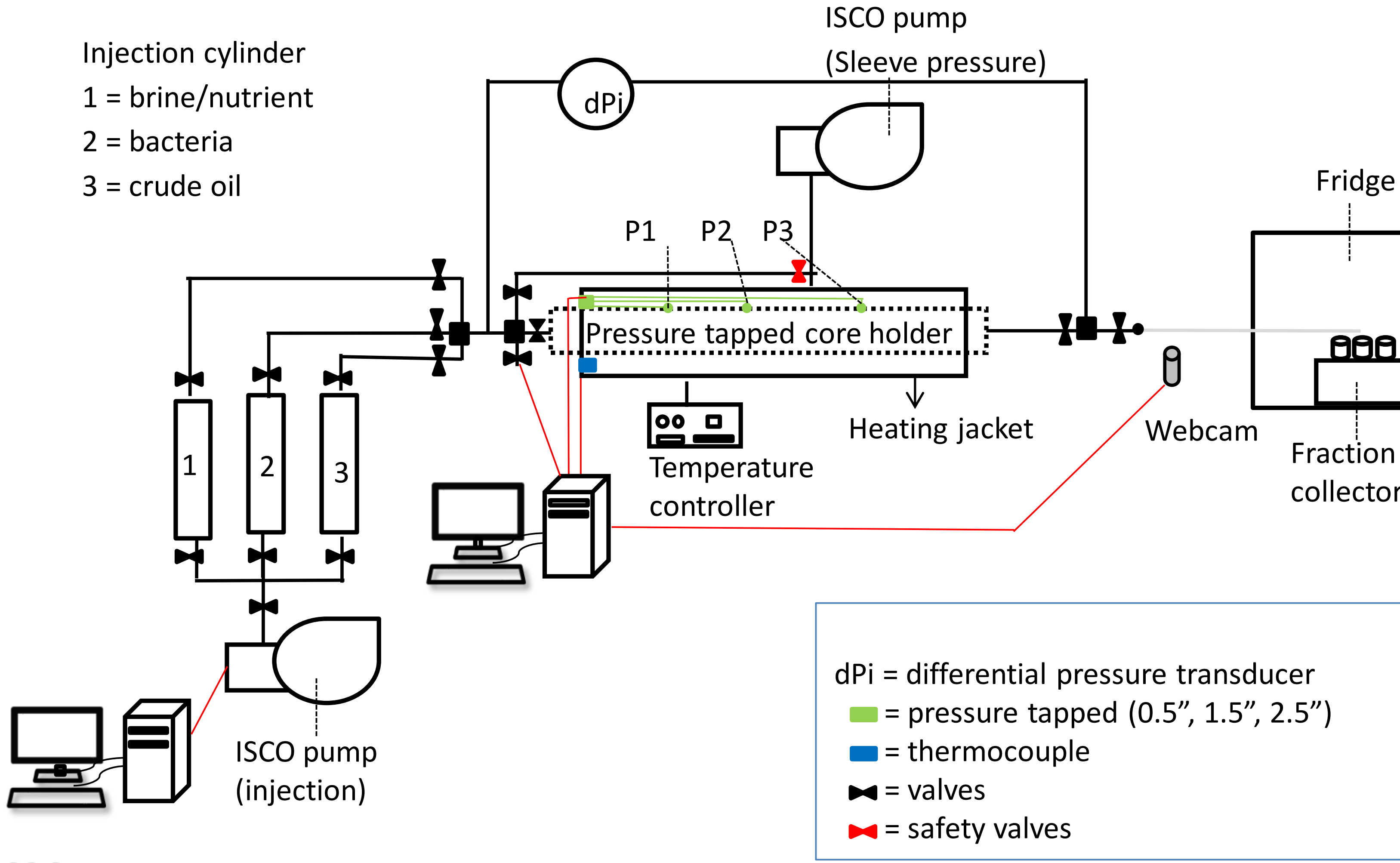
Smaller size.

Different surface properties.

Reactivation.

Methods

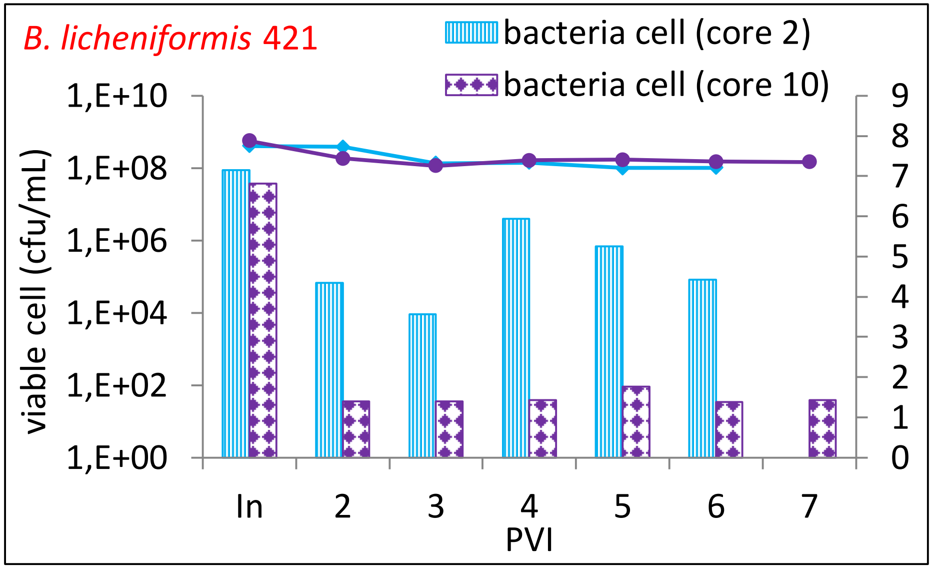
Schematic Core Flooding Set-up

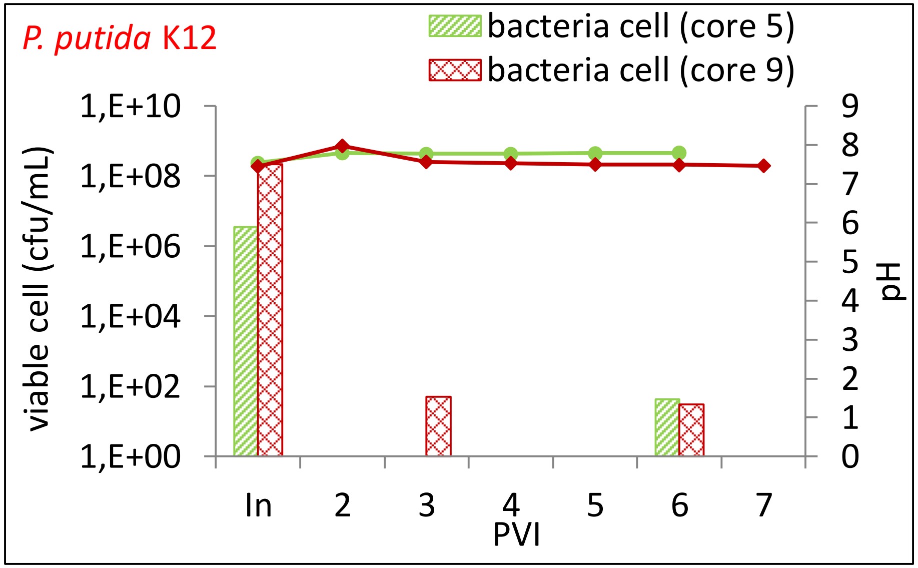


Spore-forming vs non-spore-forming

Bacteria penetration study/One phase liquid core flooding:

Halim *et. al.*, Transp. Porous Med. (2014) 101, 1–15. doi:10.1007/s11242-013-0227-x



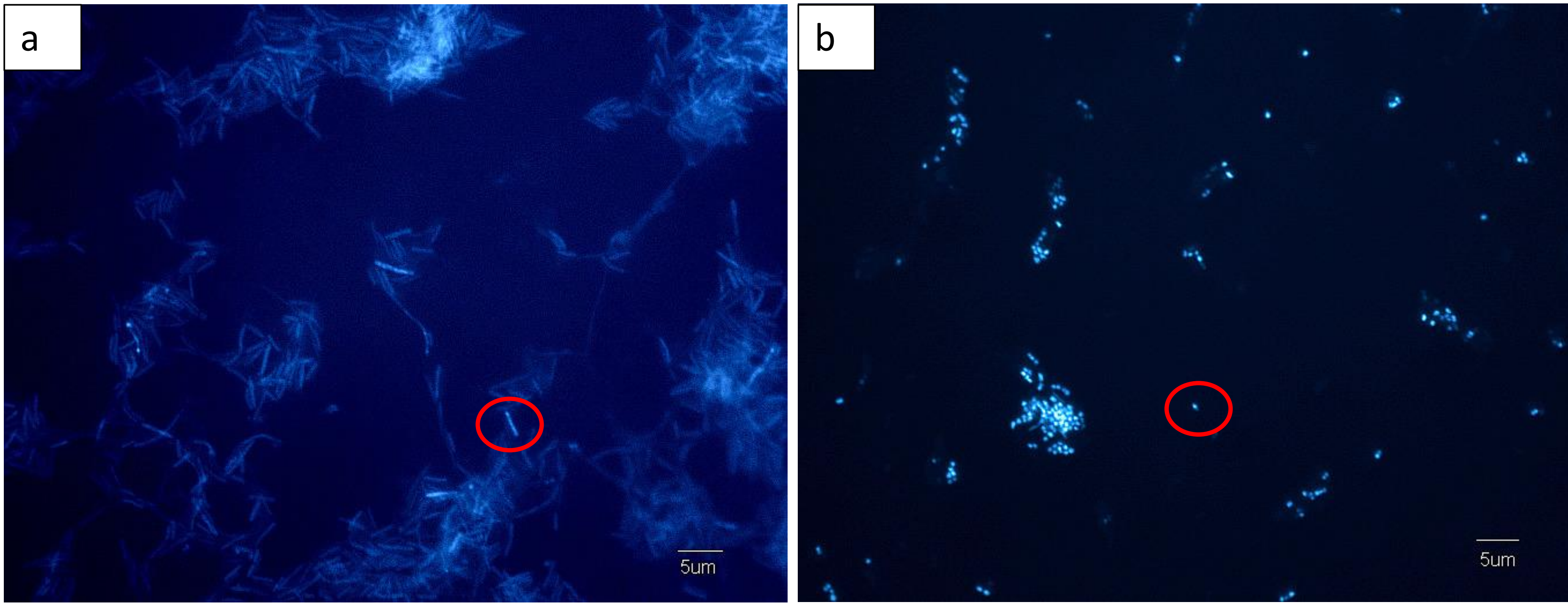


- More cells were found in the effluents of core flooding with *B. licheniformis* 421 as compared to *P. putida* K12
- Survival/motion of bacteria can be mainly due to spores.

Penetrated bacteria

Bacteria penetration study/One phase liquid core flooding:

Halim *et. al*., Transp. Porous Med. (2014) 101, 1–15. doi:10.1007/s11242-013-0227-x



B. licheniformis 421 cells under DAPI staining (a) in growth media, before injection into a chalk core plug, cell size 0.5 x 3µm (b) in the effluent from a chalk core plug, spore formation

Flooding sequences

"Tertiary recovery"

1. Injection of SS (2-3 PVI)
2. Injection of crude oil until S_{wi}
3. Injection of SS until S_{or} (1st SS)
4. Injection of bacteria (1-3PV)
5. Incubation (3 days)
6. Injection of SS (2nd SS)

Tertiary

"Secondary recovery"

1. Injection of SS (2-3 PVI)
2. Injection of crude oil until S_{wi}
3. Injection of 1PV SS (1st SS)
4. Injection of bacteria (1PV)
5. Incubation (3 days)
6. Injection of SS until S_{or} (2nd SS)
7. Injection of nutrient (1PV)
8. Incubation (7 days)
9. Injection of SS (3rd SS)

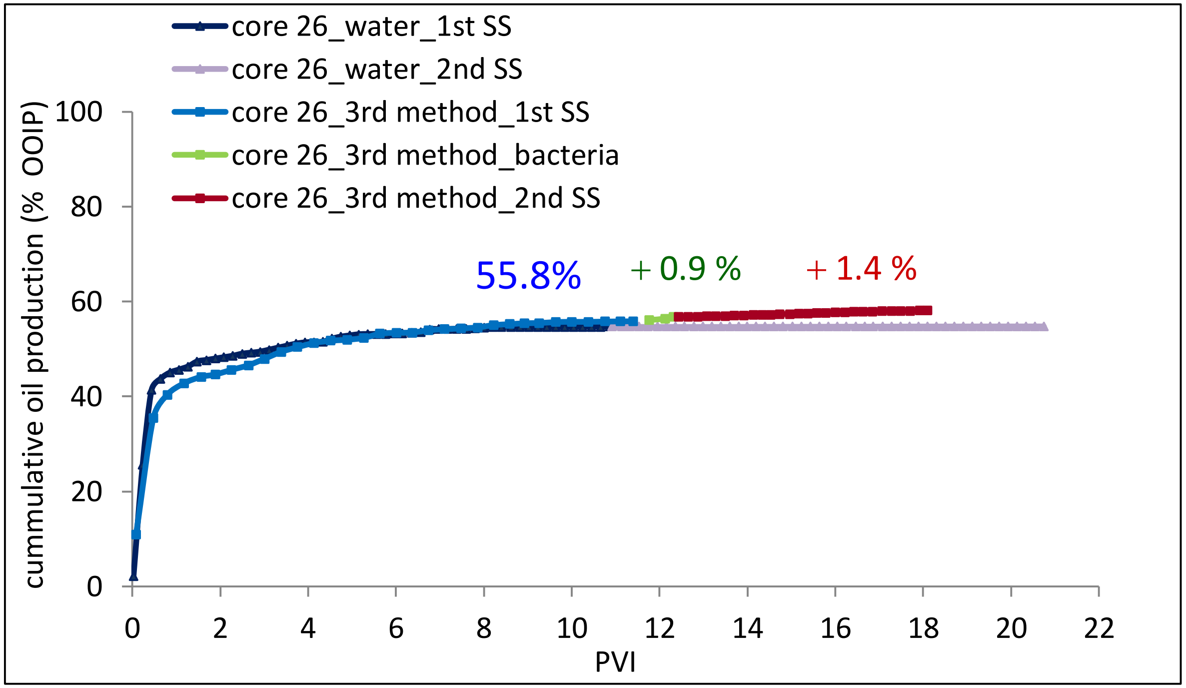
Secondary

Core plug properties

Core ID	k before (mD)	k after (mD)	ϕ before (%)	ϕ after (%)
26_water	3.2	2.8	30.8	30.7
26_3rd m	3.2	3.1	31.1	30.7
26_2nd m	3.1	3.2	30.7	30.8

- Core 26 – homogenous reservoir chalk core
- No significant change in k and ϕ before and after experiment
- No fractures based on CT scan results before and after experiments

Do bacteria produce more oil?



Core no	S_{or} (% OOIP)
26_water	45.2
26_3rd method	44.2

Samples	Viscosity (cP)
Crude oil	4.96
SS	0.55
SS+molasses+bacteria	0.55

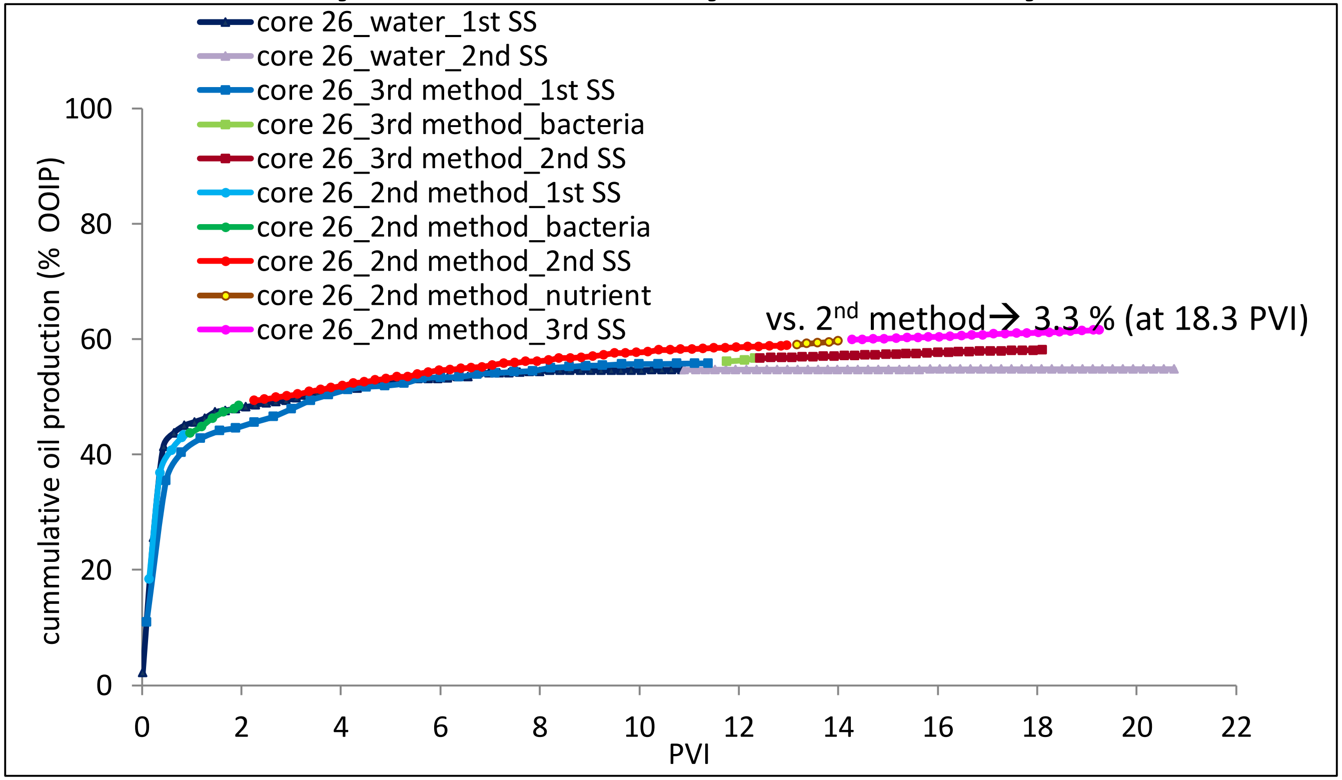
Tertiary oil recovery method with production stopped at 11.5 PVI.

1 PV bacteria injected and incubated.

Additional oil: 2.3 % OOIP.

Results

Secondary vs tertiary recovery?



Core no	Sor-1PV (%)
26_2nd method	56.7

Total oil recovery
Water : 54.8%
Bacteria_3rd : 58.1%
Bacteria_2nd : 61.6%

Secondary oil recovery method produces 3.3 % OOIP compared to tertiary method. 1 PV bacteria injected 1 PV after break-through.

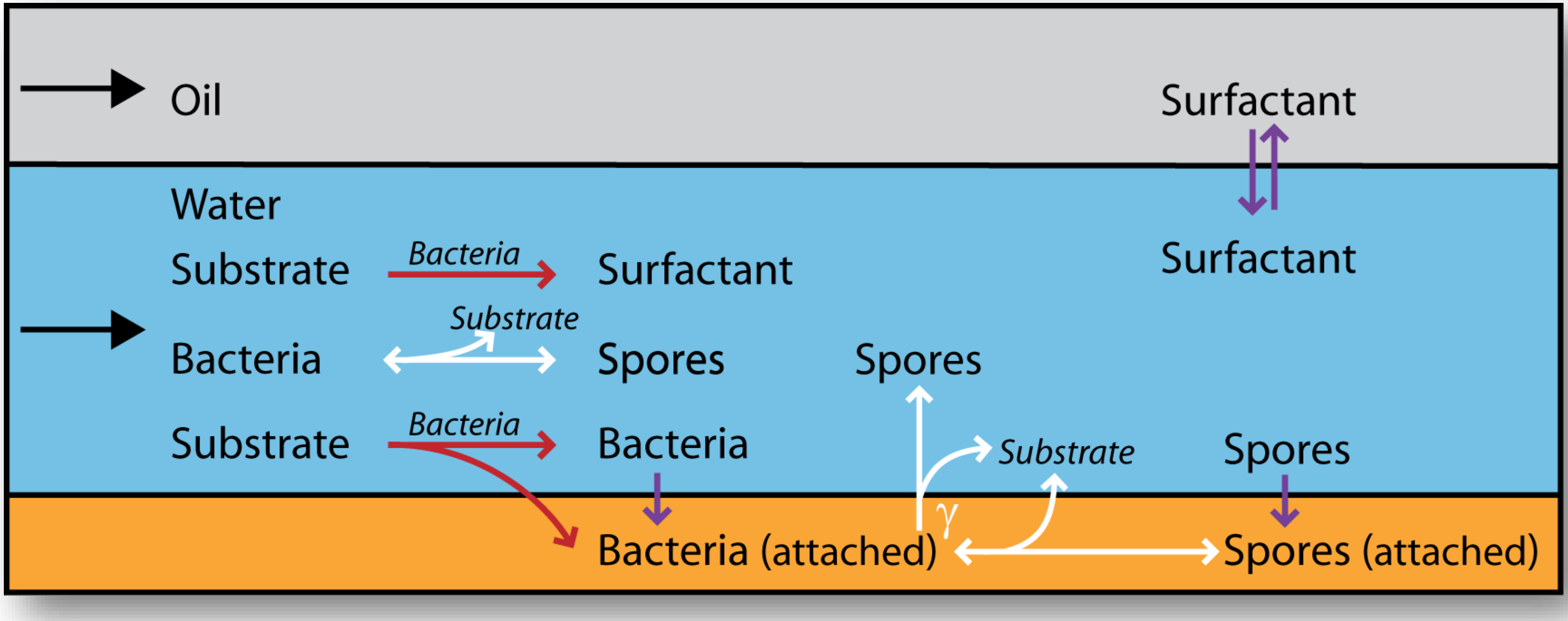
SIMULATIONS

SIMULATOR OVERVIEW

1D MEOR SIMULATOR

- Generic model.
- Growth and other reactions.
- Bacterial surfactant reducing IFT.
- Bacteria attachment due to **filtration** or equilibrium adsorption.
- **Plugging**
- **Application of spore-forming bacteria.**

1D MEOR MODEL



$$\frac{\partial}{\partial t}\left(\phi \sum_{j=1}^{n_p} \omega_{ij}\rho_j s_j\right) + \frac{\partial}{\partial x}\left(v \sum_{j=1}^{n_p} \omega_{ij}\rho_j f_j\right) = \phi q_i$$

$$i = \{o, w, b, s, m\},\ j = \{o, w\}$$

SOURCE TERMS

Attachment

Irreversible deep bed filtration.

$$r_{att} = \lambda_0 \, v \, \omega_{bw}$$

$$r_{att} = \lambda_{sp} \, v \, \omega_{spw}$$

$$\lambda_{sp} = 0.1 \lambda_0$$

Pore size vs. bacteria size.

Reaction

Bacteria, surfactant and substrate.

$$r_b = Y_{sb} \, \omega_{bw} \left(r_{max} \cdot \frac{(\omega_s \rho_w)}{K_s + (\omega_s \rho_w)} \right)$$

Sporulation

$$a_b \text{ bacteria} \rightleftarrows a_{sp} \text{ spore} + a_s \text{ substrate}$$

$$r_{ij} = K_{bs}(\omega_s) \cdot a_x \, \omega_{xy}$$

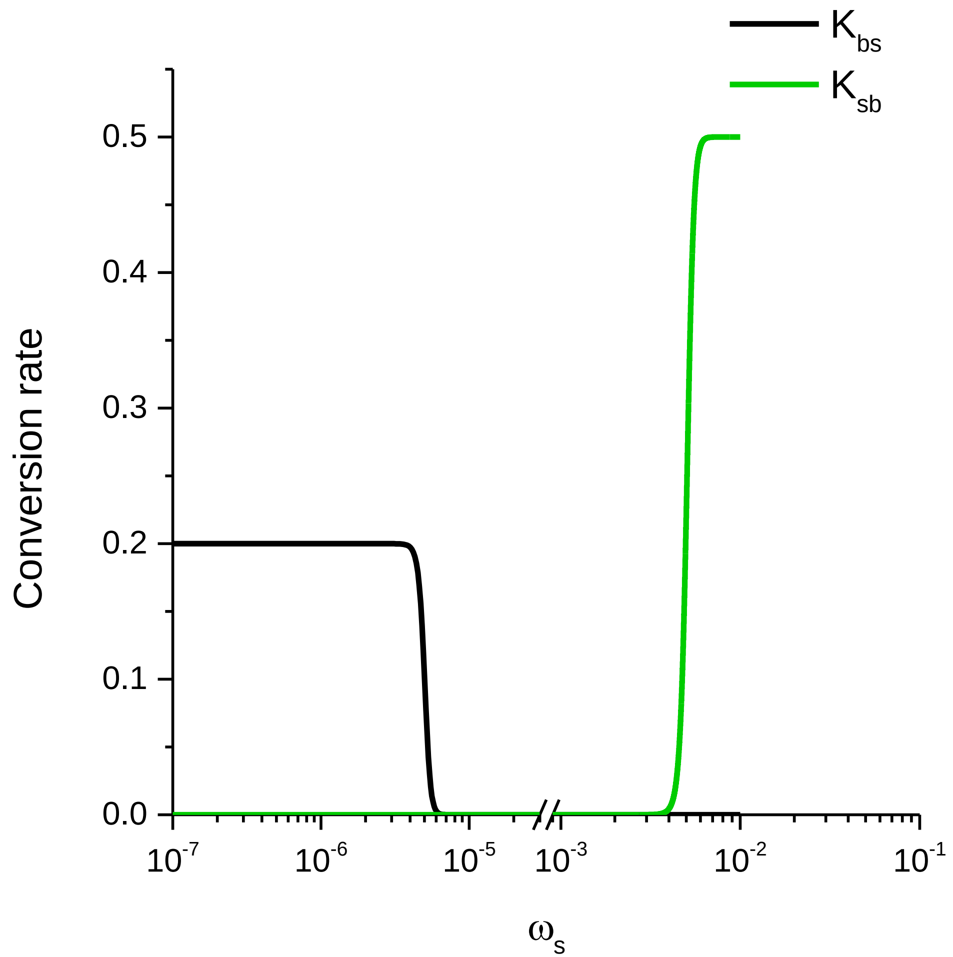
SPORULATION

Sporulation

- Sigmoid-shaped curve for stress response in bio-systems
- Conversion releases substrate.

Reactivation

- Triggered by good conditions for survival



EFFECTS

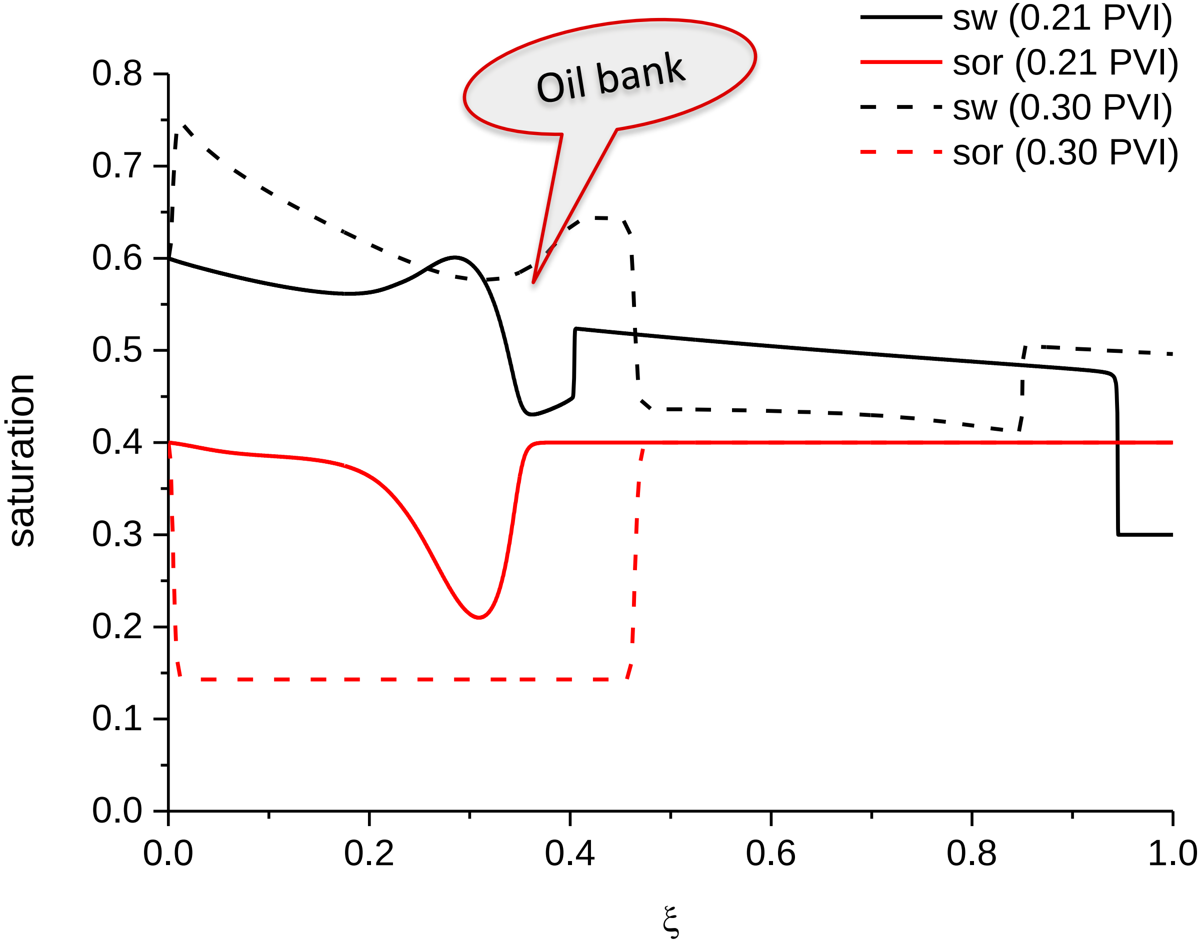
Oil mobilization

- Surfactant production
- IFT reduction
- Residual oil saturation
- Relative permeability
- Fractional flow

Option: Porosity reduction

- Attachment
- Microbial growth
- Porosity reduction
- Water relative permeability
- Fractional flow

PROFILE CHARACTERISTICS



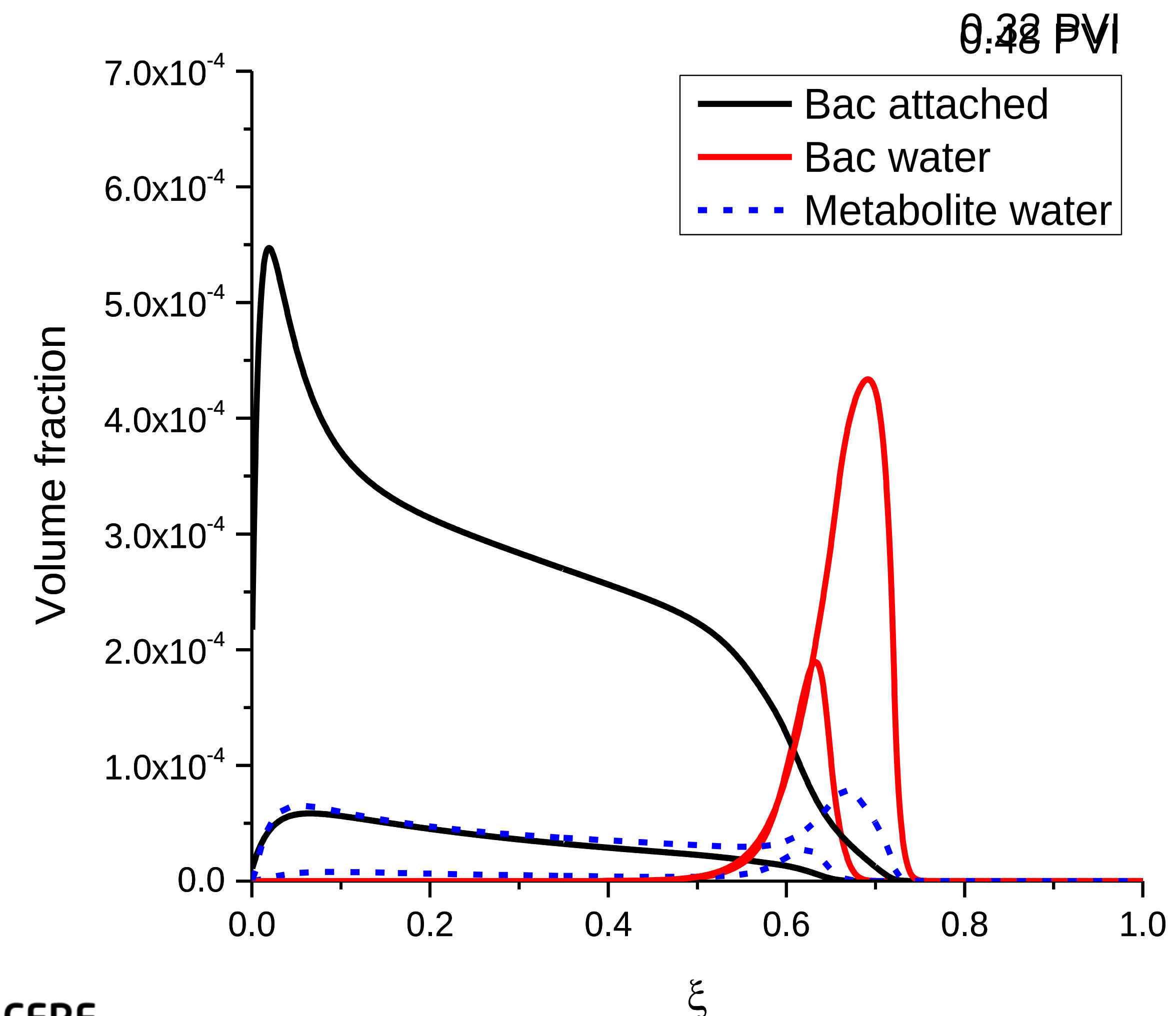
Two oil banks appear.

Injection

Constant rate.

Continuous.

RISK OF INLET CLOGGING



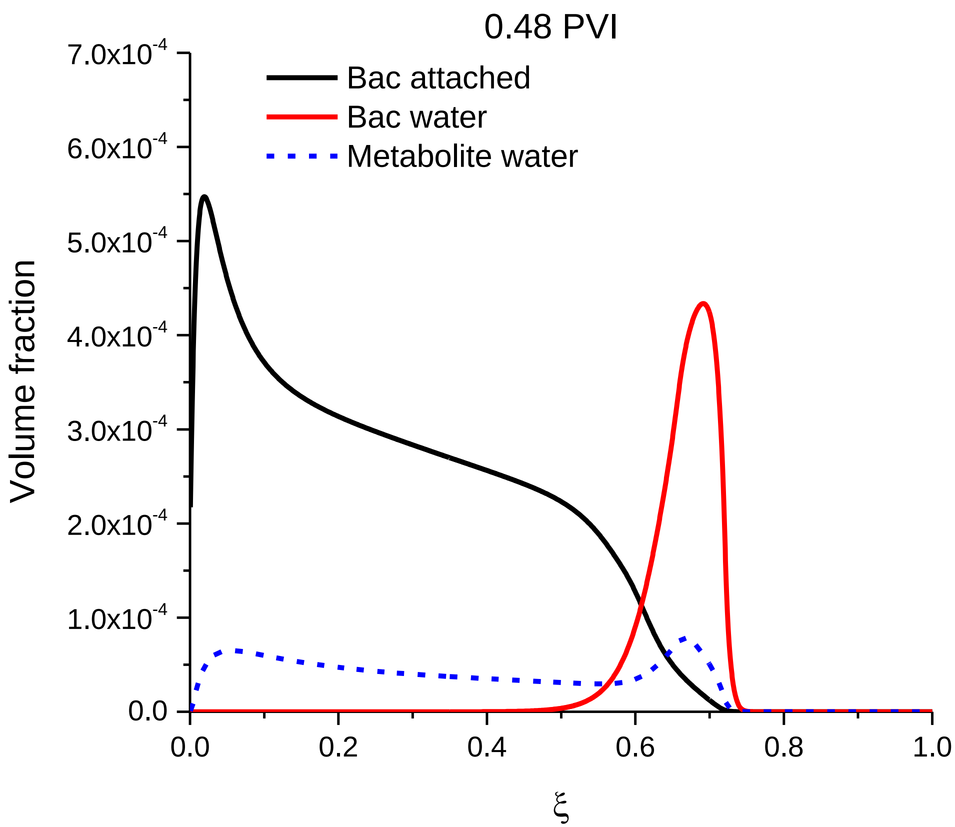
Two bacteria peaks.

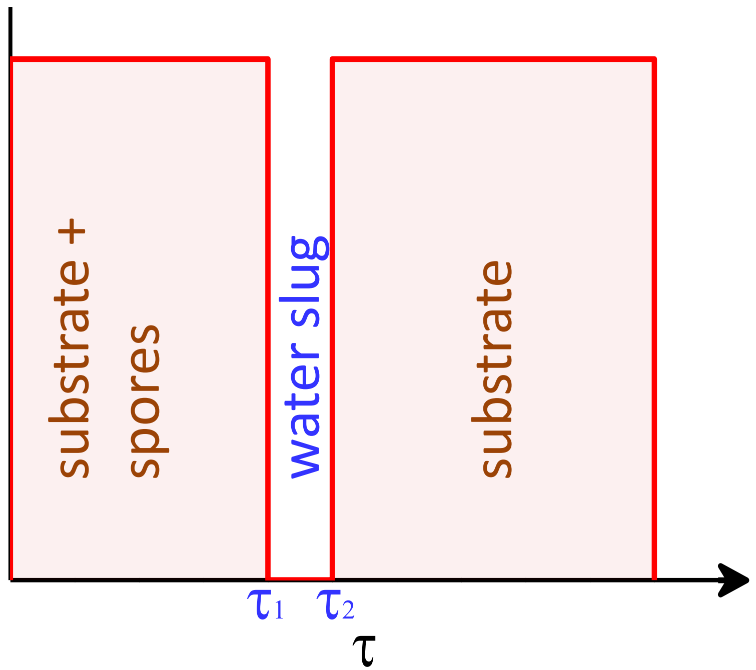
Surfactant effect.

Inlet clogging risk.

Increased recovery.

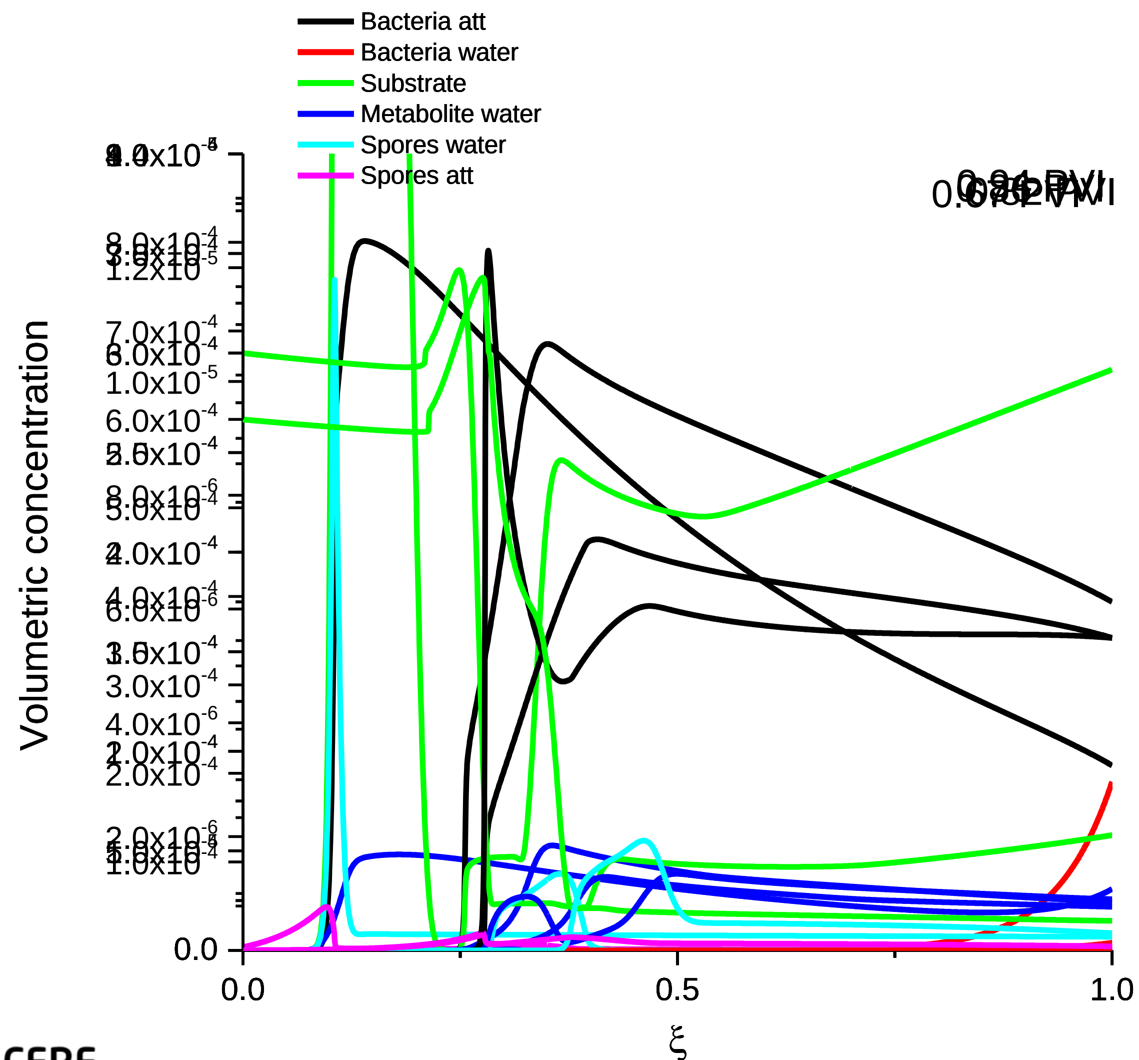
SLUG INJECTION SCHEME





Slug injection scheme selected to avoid clogging and to concentrate attached bacteria in specific zones in the reservoir.

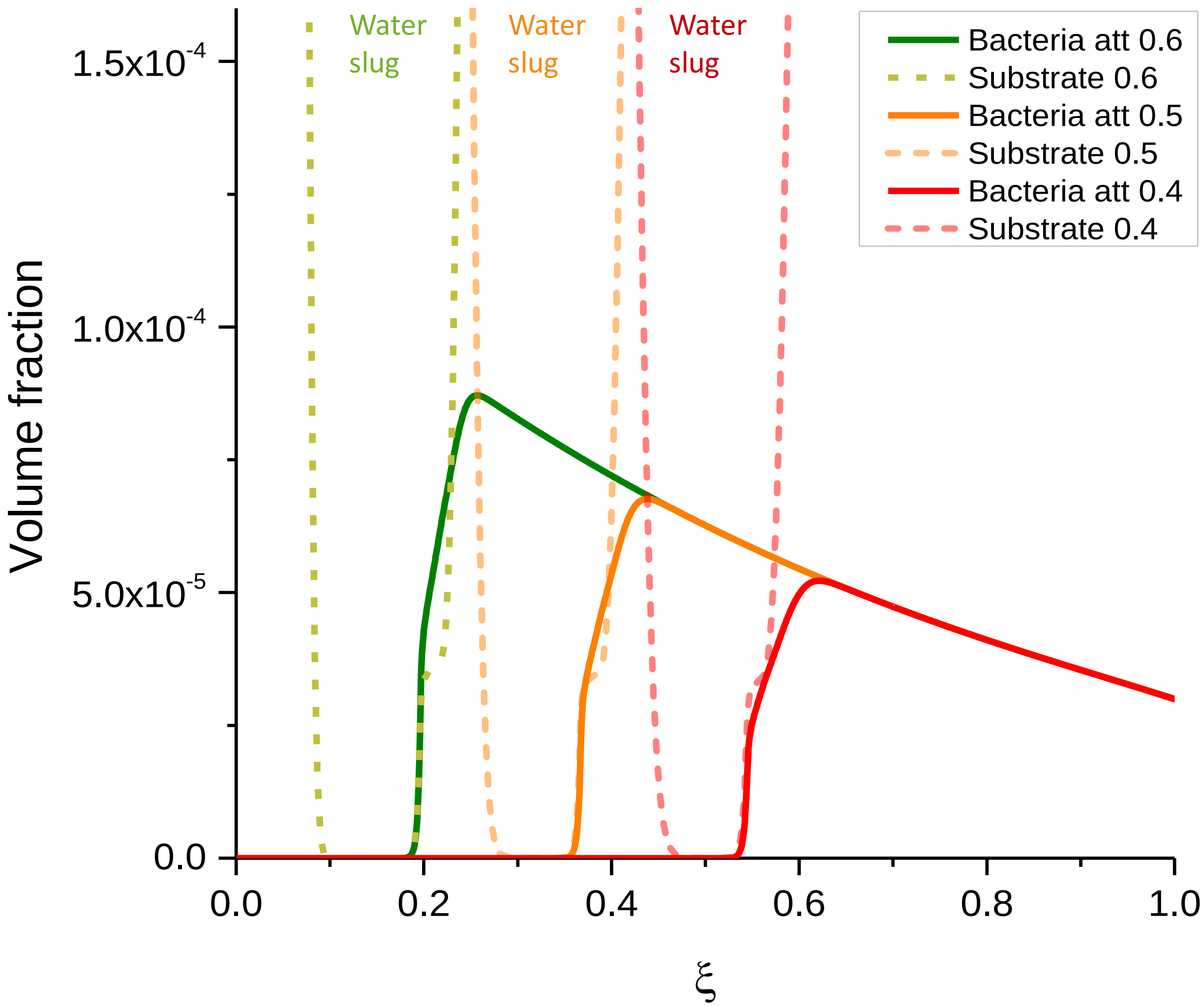
RELEASING PROCESS



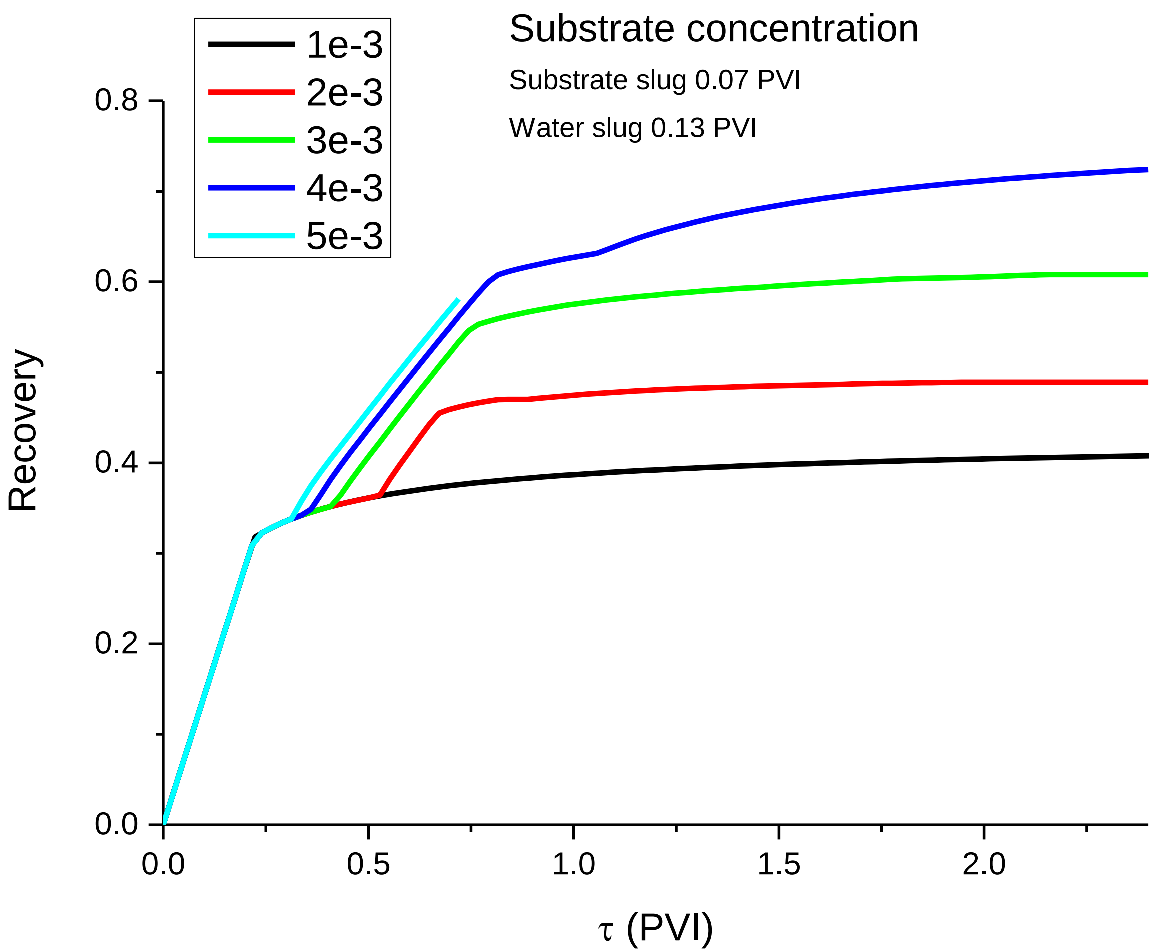
Water slug induces conversion of attached bacteria to spores.

Rate of conversion is determined by released substrate and thus bacteria concentration.

REDUCTION OF CONVERSION RATE



SUBSTRATE AND SLUGS



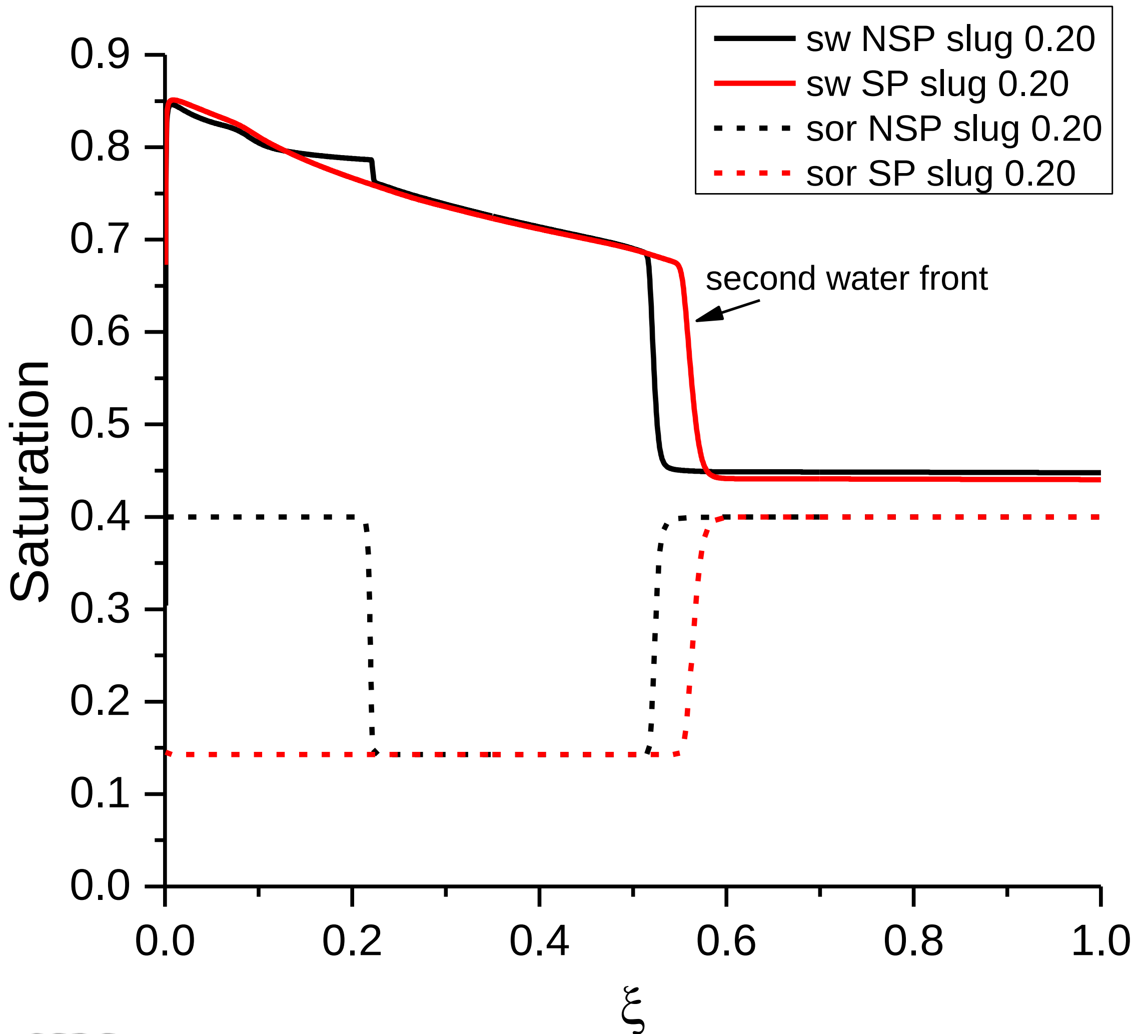
HIGH SUBSTRATE INJECTION CONCENTRATION

Faster MEOR response

Spore injection and spore-forming bacteria injection are similar

Waterflooding curve corresponds to 1e-3 curve.

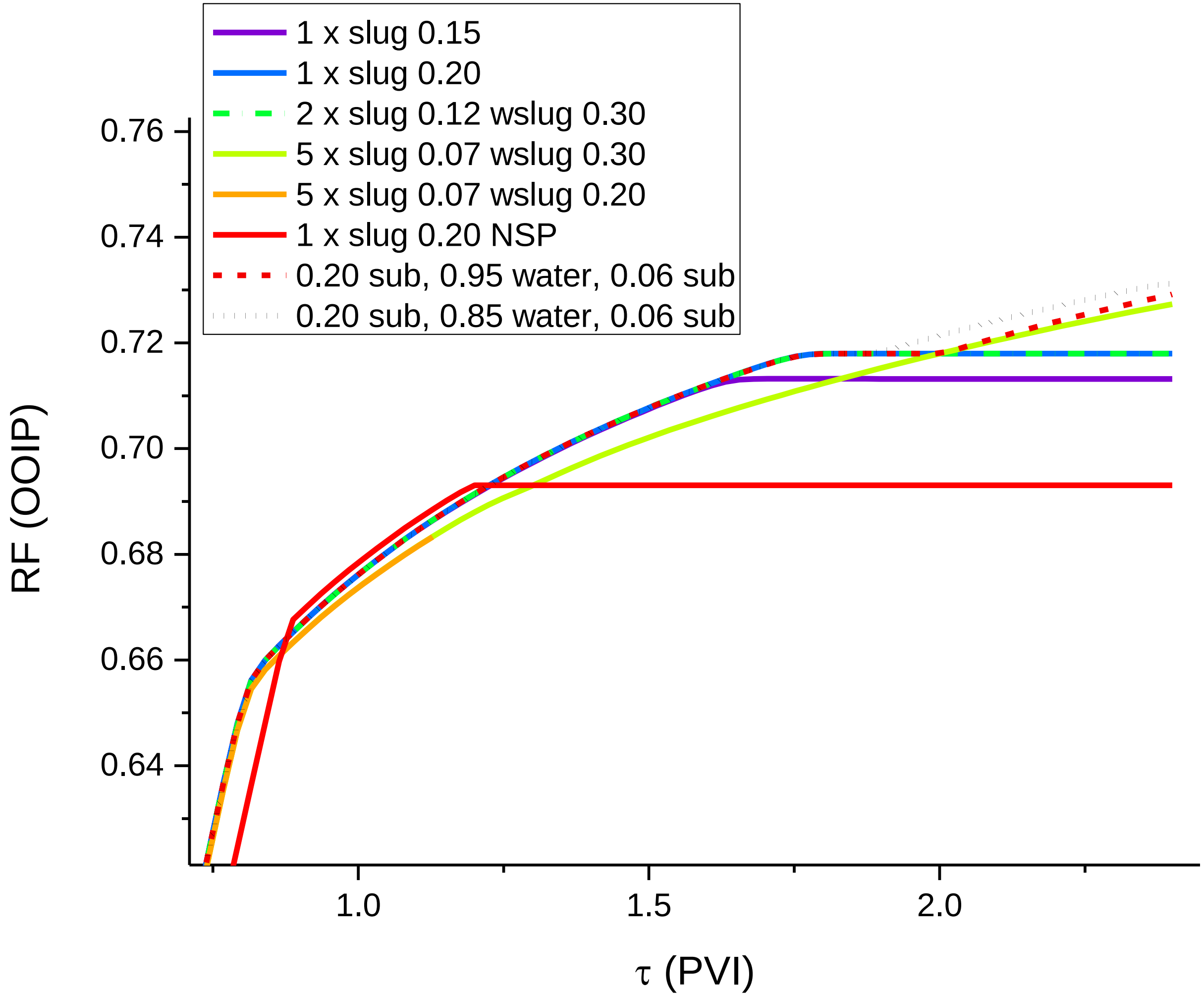
SPORE-FORMING BACTERIA



SLUGS

- Reduced clogging risk
- Larger surfactant production
- Improved utilization of substrate
- Prolonged oil mobilization

SLUG INJECTION SCHEMES



High substrate injection concentration.

First slug is important for final recovery.

Improved utilization of substrate injected.

CONCLUSION

- Spore-forming bacteria penetrate tight chalk better and may be used for MEOR.
- Experimental discoveries lead to new MEOR features to investigate numerically:
  - Filtration type behavior (no biofilms)
  - Spore formation
  - Selective plugging

CONCLUSION

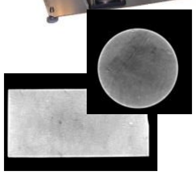
- Numerical simulations show that spore-forming bacteria have the potential to avoid clogging due to sporulation.
- High substrate injection concentration gives fast MEOR response.
- Prolonged oil mobilization with water slugs due to substrate release from sporulation of attached bacteria.
- It is possible to optimize the recovery by selecting right slug sizes and sequences
- It is possible to deliver spores to a certain point at the reservoir and make them plugging there.
- The first slug is the most important for final recovery.

Thank you for your attention.

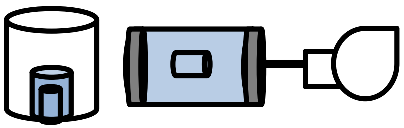
QUESTIONS?

Methods

Core Flooding Experimental Flow Chart

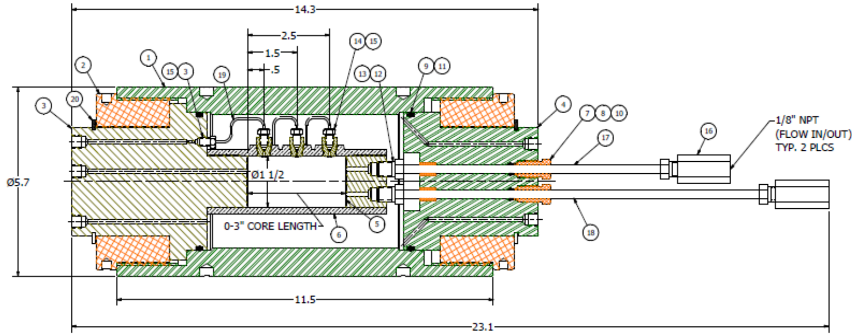


Measurement of k and ϕ, CT scan

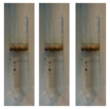


Core plug saturation under vacuum and high pressure

Core plug: Cleaning



Effluent



Measurement of oil produced

Bacterial counting

Methods

Different studies:

Tertiary

1. Injection of SS (2-3 PVI)
2. Injection of crude oil until S_{wi}
3. Injection of SS until S_{or} (1st SS)
4. Injection of bacteria (1-3PV)
5. Incubation (3 days)
6. Injection of SS (2nd SS)

Secondary

1. Injection of SS (2-3 PVI)
2. Injection of crude oil until S_{wi}
3. Injection of 1PV SS (1st SS)
4. Injection of bacteria (1PV)
5. Incubation (3 days)
6. Injection of SS until S_{or} (2nd SS)
7. Injection of nutrient (1PV)
8. Incubation (7 days)
9. Injection of SS (3rd SS)

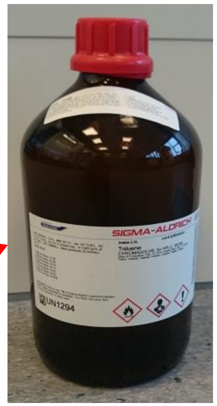
Wettabillity

1. Injection of SS (2-3 PVI)
2. Injection of crude oil until S_{wi}
3. Aging – 3 weeks
4. Injection of crude oil (2-3 PVI)
5. Injection of SS until S_{or} (1st SS)
6. Injection of bacteria (1-3PV)
7. Incubation (3 days)
8. Injection of SS (2nd SS)

Methods

Oil Measurement (Evdokimov et. al., 2002)

Effluent (oil in brine)



Add 3ml toluene

Hand shake to dissolve the oil

Let the oil in toluene and brine seperate into two phases

Upper phase (oil in toluene) was decanted to a silica glass cuvette

Measure at UV-vis spectrophotometer at λ=750 nm

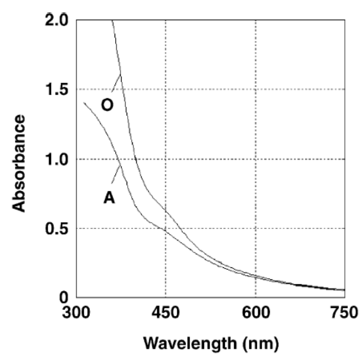
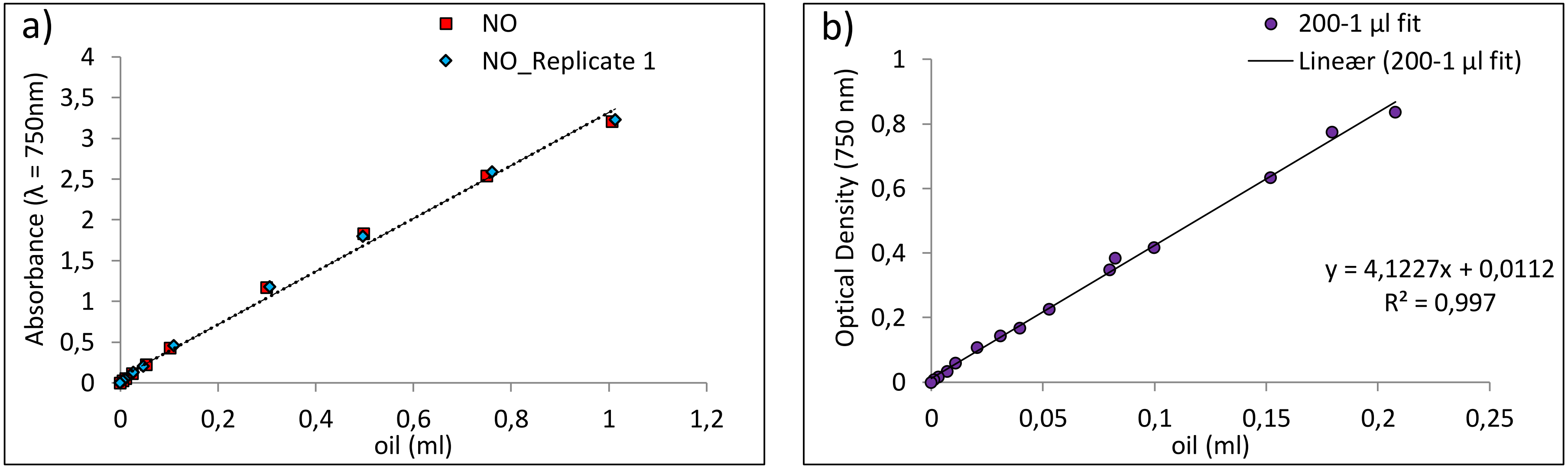


Fig. 2. The absorption spectra for toluene solutions of Tatarstan solid asphaltenes (A) and of a Tatarstan crude oil (O). Both asphaltene concentrations are close to 66 mg/l.

Results

UV-vis method



- The UV/visible spectroscopy method relies on absorptivities of solid asphaltene aggregation in toluene solution.
- Fig. a shows good linear regression of the NO concentration vs. the absorbance data. The replicate samples showed similar linear regression trend line which means this method is quite stable and reproducible.
- This method can detect oil as low as 1 µl (Fig. b).

Results

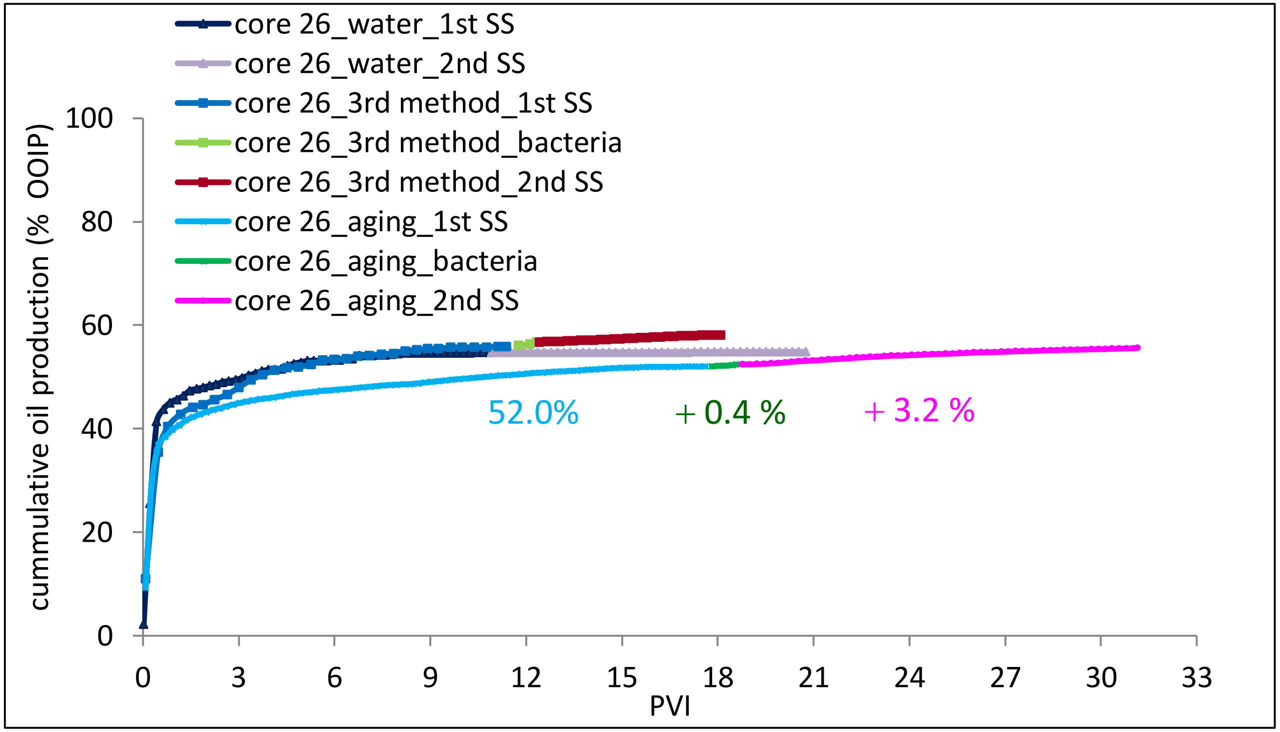
Core Plugs Properties

Core ID	k before (mD)	k after (mD)	ϕ Before (%)	ϕ after (%)
26_water	3.2	2.8	30.8	30.7
26_3rd m	3.2	3.1	31.1	30.7
26_2nd m	3.1	3.2	30.7	30.8
26_aging	2.8	3.1	30.7	30.6

- Core 26 – homogenous reservoir chalk core
- No significant change in k and ϕ before and after experiment
- No fractures based on CT scan results before and after experiment

Results

Wettability alteration?

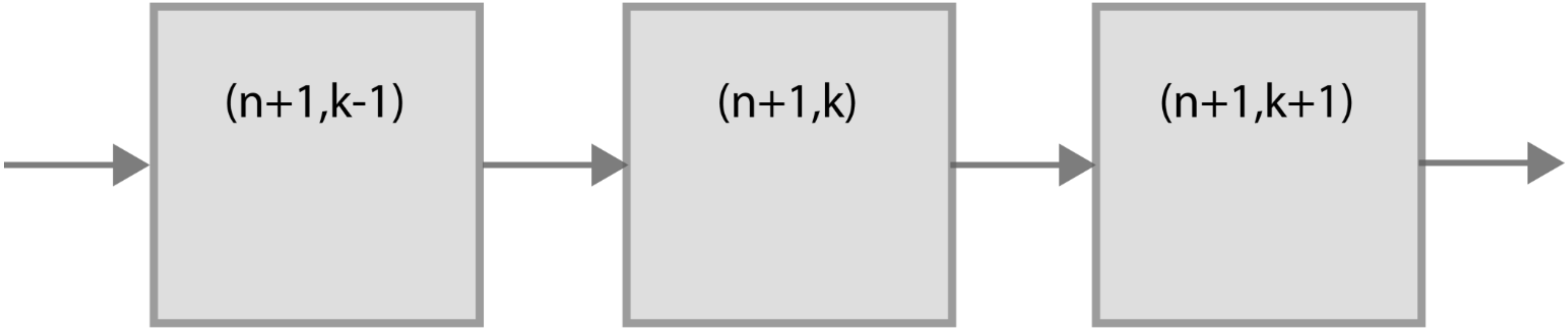


Core no	S_{or} (% OOIP)
26_aging	48.6

Total oil recovery:
Aged core : 55.6%

- Experiment with an aged core gave 3.6% incremental oil, very slightly higher than non-aged core

NUMERICAL SOLUTION



Tanks-in-series approach

Multivariable Newton iteration

Sequential procedure