Improved Oil Recovery by Waterflooding and Spontaneous Imbibition

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Petrophysics and Surface Chemistry Group
Chemical and Petroleum Engineering

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Overview of Projects*

- Spontaneous Imbibition – Fractured reservoirs
- Improved waterflooding
- Fundamentals of forced displacement, spontaneous imbibition, capillary pressure vs saturation
  Capillary pressure drainage and imbibition measurements, interfacial areas, surface roughness and interface curvatures (theory/experiments)
  UW: Behrooz Raeesi (presently intern with BP Alaska), Yifan Zhang
  MicroCT measurements of interfacial areas and curvatures
  ANU: Adrian Shepherd, Jill Middleton

*Publications and presentations are listed at http://wwweng.uwyo.edu/economic/psc/publications.htm
Research Progress

Spontaneous Imbibition

- Scope of work
- MRI imaging of development of an imbibition front

Theory: Geoff Mason; U Manitoba: Doug Ruth
MRI Imaging: ConocoPhillips: James Howard, Jim Stevens
Radioactive tracer imaging: U Bergen: Martin Ferno, Asmund Haugue, Arne Graue

Improved waterflooding

- Low salinity waterflooding – background and status
- Comparison of CBM waterflooding of Phosphoria reservoir vs outcrop dolomite - Extension of previous work on Tensleep and Minnelusa Eolian sandstone
- Capillary number and microscopic displacement efficiency
- Sequential waterflooding - no change in brine composition

ANU: Andrew Fogden, Mark Knackstedt, Tim Senden, Evgenia Lebedeva, Munish Kumar

Future Work
Spontaneous Imbibition

*Key Mechanism for Oil Recovery from Fractured Reservoirs*

- pore level modeling of imbibition (experiment and theory)
- direct measurements of capillary pressure driving force
- correlations (core properties, characteristic lengths, viscosity ratios, wettability)
- imaging of displacement fronts (MRI /ConocoPhillips, nuclear tracers/ Univ Bergen)
- enhanced oil recovery from oil wet rocks by imbibition of surfactant solutions
- enhanced imbibition by low salinity water
- role of capillarity/gravity forces
MRI Imaging of One – End Open (OEO) Imbibition

Whitestone Upper Zone (UZ) Limestone

No-Flow Surface

No-Flow Boundary

OEO
One – End Open

\[ L_c = x \]
Recovery of n-Decane by One-End Open (Linear) Imbibition for Whitestone UZ
Average Frontal Distance of One-End Open (Linear) Imbibition for Whitestone UZ
Some Key Conclusions

Once an imbibition front is established, the imbibition process can be modeled as a piston displacement.

In contrast, simulation of spontaneous imbibition using relative permeability and capillary pressure functions predicts that the frontal region will grow as imbibition progresses (as will a self-similar front).

Operative relative permeabilities for counter-flow of oil and water during imbibition depend on the viscosity ratio.
Low salinity waterflooding (LSW)
June 1995 – The British Petroleum Research Center sent their representative, Cliff Black, for a three day “think tank” session that brought focus to low salinity waterflooding.
Interest in LSW has increased as indicated by the number of publications and presentations on LSE.

Recent UW Activities


Low Salinity Waterflooding at $S_{wi}$

*First observations*
Waterflood recovery vs. pore volume (PV) showing LSE for LSW at $S_{wi}$. Connate and injection have identical ionic concentrations. Experiments were conducted in matched Berea sandstones core plugs.
Application of LSW of Most Current Interest

Watered-out reservoirs at residual oil saturation, $S_{or}$, after HSW.
Distinct advantage of demonstrating LSE in a single core.
Field Pilots of LS@Sor

Improved oil recovery observed
- McGuire, P. et al., SPE 93903 (BP 2005)
- Seccombe, J. et al., SPE 113480 (BP 2008)
- Seccombe, J. et al., SPE 129692 (BP 2010)

No response
- Skrettingland, K. et al., SPE 129877 (Statoil 2010)

Consistency of lab tests and field results was observed for both good and bad prospects – encouraging with respect to screening LS candidates,
Mechanism?

Many laboratories and organizations have grappled with identifying, reproducing, and explaining LSE.

Despite growing interest in LSE, a consistent mechanistic explanation has not yet emerged.
Necessary Conditions for LSE

* Tang and Morrow (1999) *

- a significant clay fraction,
- the presence of connate water, and
- exposure to crude oil to create mixed-wet conditions.

*These conditions are not sufficient.*
Mechanism - Limited Mobilization of Fine Particles (Kaolinite)

Tang and Morrow, JPSE, 1999

There are now numerous examples of LSW for whichproduction of fine particles is not observed.

However, the number of submicron particles in sandstone thatchange location during waterflooding has been demonstrated to increase with decrease in salinity (Fogden, Kumar, Morrow, Buckley, Energy & Fuels 2011).
SEM imaging: Single-phase flooding

Berea B1 “Before”: 97x73 μm², scale bar 10 μm
Berea B1 “After”: 97x73 μm², scale bar 10 μm
Wettability Alteration

Wettability alteration, usually towards increased water-wetness during the course of low salinity flooding, is the most frequently suggested cause of increased recovery.

Rate of spontaneous imbibition is the most direct measure of wettability.
• comparable initial rates of imbibition are measured in all three cases
• the extent of imbibition increases significantly with decrease in salinity.

Explaining the increases in microscopic displacement efficiency observed for both spontaneous imbibition and waterflooding is key to understanding LSE.
Progress in Identification of Mechanisms through Systematic Tests

Requires a reliable supply of a uniform model rock that shows LSE. (Preferably at least 6% OOIP increase for LS @ $S_{or}$)

17 sandstones and 7 outcrop carbonates are being tested for LS response
Outcrop Rocks tested for low salinity response (limestone shown in blue)
Examples of LSW @ Sor

Briar Hill - R1 (WP Crude Oil)

\[ \begin{align*}
\text{Kg} &= 5.6 \text{ D} ; \text{kb} = 706 \text{ mD} \\
S_{wi} &= 27\% 
\end{align*} \]

Berea Kc - R1 (WP Crude Oil)

\[ \begin{align*}
\text{Kg} &= 224 \text{ mD} ; \text{kb} = 232 \text{ mD} \\
S_{wi} &= 25\% 
\end{align*} \]
Mobilization of oil at HS $S_{or}$ by LSW

\[ \Delta S_{oe} = \frac{S_{o\text{ Hisal}} - S_{o\text{ Losal}}}{S_{o\text{ initial}} - S_{o\text{ Hisal}}} \times 100\% \]
Summary

• Overall, reservoir rocks respond better to LS flooding than outcrop rocks

• Identification of the sufficient conditions for LSE remains as an outstanding challenge.

• Field wide application of LS flooding is being implemented

• There are now ongoing tests on applying LS flooding at Swi (the outset of reservoir development)
Optimization of injection brine compositions 
(*both low and high salinity*)

Much improved engineering of waterfloods will result from development of broad understanding of the factors that determine waterflood recoveries for crude oil/brine/rock combinations for wide ranges of ionic strength and composition.

“smart water” “designer brines” “optimized brines”
Dissolution of Minerals

Increased recovery in response to LS has been demonstrated for Wyoming sandstone and carbonate cores containing anhydrite.
Studies on Wyoming Reservoirs using Low Salinity - Coal Bed Methane Water  
Pu, Xie, Yin, Morrow, SPE 134042, 2010

• Minnelusa (Gibbs) and Tensleep (Teapot Dome) eolian sandstones
  ❖ One half of Wyoming’s oil production
  ❖ Abundant dolomite & anhydrite cement

• Phosphoria (Cottonwood Creek) dolomite formation
  ❖ Recovery factor less than 10%
  ❖ Patchy anhydrite
Low Salinity Waterflooding for Phosphoria Rock

Pu et al., 2010
Silurian Dolomite Outcrop

Mineralogy: interstitial dolomite and *no anhydrite*

Porosity: 17 – 20%

Permeability: 100 mD – 1,000 md
Low Salinity Waterflooding for Silurian Dolomite Outcrop

Silurian Dolomite (WP Crude Oil)

\[ T_a = 60^\circ C \quad T_d = 60^\circ C \]
\[ k_g = 102 \text{ mD} \quad k_b = 19 \text{ mD} \]
\[ S_{wi} = 24\% \]
Further tests on Silurian dolomite related to presence of sulfate

- No significant increase in recovery when injection was switched to LS calcium sulfate solution
- No increase in recovery after deposition of anhydrite within a core by oven drying (LS/LS or HS/LS)
Summary

- Tensleep and Minnelusa sandstones, and Phosphoria dolomite all contained anhydrite and all responded to low salinity waterflooding.

- Outcrop Silurian dolomite (and also Tensleep sandstone from an aquifer) did not show anhydrite and did not respond to low salinity waterflooding.

- Addition of sulfate to either the injection brine or the rock did not improve recovery from the Silurian dolomite.
Increased Oil Recovery by Low Salinity Waterflooding and Change in Capillary Number through Increase in Flood Rate ($v$) and Injection of Viscous Brine ($\mu$)

$$N_{Ca} = \frac{v\mu}{\sigma} \quad (\sigma: \text{IFT})$$

(data obtained for outcrop sandstone observed to be responsive to low salinity waterflooding provided by Total)
Increase in Capillary Number by increase in flood rate after Low Salinity Waterflooding
Total Du3 E7/Total A crude oil ($\mu_o = 3.5$ cP)

Aqueous phase: 0.59 cP

\[ \Delta P, \text{ psi} \]
\[ R, \% \text{OOIP} \]

0.25 mL/min 0.25 mL/min 1.0 mL/min

SW2 20x dilution
2,898 ppm

SW2 57,951 ppm

1.8x

$K_{air}$ = 698 mD; $\phi$ = 19.5%

$S_{wi} = 18.0\%$
Increase in Capillary Number by increase in brine viscosity (HS) after Low Salinity Waterflooding
$K_{\text{air}} = 788 \text{ mD}; \phi = 19.7\%; S_{\text{wi}} = 16.2\%$

Total Du3 E5/Minnelusa crude oil ($\mu_0 = 16.8 \text{ cP}$)

Aqueous phase: 0.25 mL/min

- SW2 (57,951 ppm, 0.59 cP)
- SW2 20x dilution (2,898 ppm, 0.59 cP)
- SW2 in 60% glycerol solution (57,951 ppm, 4 cP)

Oil Recovery (R), % OOIP vs. Brine injected, PV

Pressure drop ($\Delta P$), psi vs. Brine injected, PV
Total Du3 E8/Total A crude oil ($\mu_o = 3.5$ cP)
Aqueous phase: 0.25 mL/min

57,950 ppm; 0.59 cP
2,898 ppm; 0.59 cP
23,180 ppm; 4 cP
3.75-5x
57,950 ppm; 0.59 cP

stopped for 14 hrs

$K_{air}=933$ mD; $\phi=19.9\%$
$S_{wi}=15.8\%$
Injection of viscous brine at reduced capillary number

(no change in salinity)
Berea PH5-2/Minnelusa crude oil
\((\mu_0 = 19.1 \text{ cP})\)
Aqueous phase: 35,593 ppm

\[ \Delta P, \text{ psi} \]

\[ R, \% \text{ OOIP} \]

\[ K_{\text{air}} = 276 \text{ mD}; \phi = 18.6\%; S_{\text{wi}} = 26.4\% \]

SW1 in 80\% glycerol solution
12.6 cP

0.05 mL/min
0.25 mL/min
1.00 mL/min
3.00 mL/min
0.05 mL/min
0.25 mL/min
1.00 mL/min
stopped for 16.5 hrs
stopped for 26.1 hrs

2.86x
4.75x

\[ \Delta P \]

3.74x
3.56x
2.81x
Summary

• Increase in capillary number by increase in injection brine viscosity always improved recovery

• Approximately equivalent increase in capillary number by increase in flooding rate usually had minor, if any, effect on recovery

• Increase in aqueous phase viscosity gave improved Microscopic Displacement Efficiency even for a Newtonian liquid

  (increase in MDE for polymers has been ascribed to visco-elastic effects)
Sequential waterflooding

• An unexpected outcome of repeated use of individual cores in study of LS waterflooding was that each test could significantly alter the outcome of subsequent tests.

• Increased recovery could not be ascribed unequivocally to LSE.
Baselines for assessment of improved oil recovery?

No previous study of reproducibility of consecutive floods of recovery of crude oil had been reported
Outcrop Bentheim Sandstone
(*very low clay content*)

Sequential Flooding *without Restoration* and *No Change in Salinity* between Cycles

- $T_a = 75^\circ \text{C}$
- $t_a = 14 \text{ days}$
- $T_d = 60^\circ \text{C}$
Sequential flooding of Bentheim sandstone (Bth 01) with seawater
Residual oil for sequential waterflooding for displacement of WP crude oil at 60°C
Two UW patents granted - Field Test ? 2011 ?

Discussion of potential field test on Oct, 13\textsuperscript{th} 2010 with James Seccombe and Scott Digert (BP Alaska)

- Extended reservoir conditions floods confirmed sequential effect (Total)
- Discussions held on watered out field in Texas that contains substantial reserves
- Presentation (NRM) on field testing at EAGE IOR Cambridge, April 2011.
- Follow up laboratory tests on a target reservoir by a service company in the UK are currently in progress.
- Presentation planned for UW EORI IOR meeting, Jackson, Sept. 12, 2011.
Effect of Crude Oil on Sequential Flooding

Tests have recently been extended to recovery of Minnelusa crude oil
Sequential flooding of Berea sandstone with Minnelusa crude oil at elevated temperature
Observations on deposition from Tensleep, Minnelusa, and WP crude oil onto kaolinite

Summary

• Sequential waterflooding *without* change in salinity *usually* showed sequential reductions in residual oil saturation.
• Publications on the mechanism of sequential flooding are in preparation.
• Further investigation of recovery of different crude oils by sequential waterflooding is needed in combination with deposition studies on clay and quartz surfaces.
• Single-well field testing of sequential waterflooding is justified
• Application to residual oil zones should be tested
Future Work

1. Test outcrop sandstones that showed incremental reduction in $S_{or}$ for response to low salinity waterflooding starting at $S_{wi}$.

2. Test sequential flooding with special emphasis on different crude oils.

3. Continue campaign for field testing of sequential flooding.

4. Drainage/imbibition capillary pressure; theory and experiments on surface energy, wetting, and roughness. (Behrooz PhD)

5. Finalize results on spontaneous imbibition and their interpretation. *Results for two-ends-open imbibition will be presented at SCA meeting in Austin, TX, Sept. 2011*

6. Carbonate initiative – potential joint project with ANU