Oil Recovery from Bakken Shale by Miscible CO$_2$ Injection

2016 SCCS Annual Meeting

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Agenda

- Project motivation & objective
- Miscible CO$_2$ EOR
- Coreflood experiments with tomographic imaging
- Simulation of miscible CO$_2$ injection
- Future work
Project Motivation

- One of the most productive tight oil plays in North America
  - Technically recoverable oil: 7.4 billion STB

- Low primary recovery factor: 5 to 10%
  - Rapid decline in production after initial peak

- EOR is a necessary step to efficiently explore unconventional liquids-rich reservoirs
Choice of EOR Technique for Bakken

- Reservoir depth: ~9,000 to 10,500 ft (2,743 to 3,200 m)

- Oil viscosity: 0.15 – 0.45 cP @ Reservoir Conditions

- Light crude oil from 36 to 48 º API

- Reservoir temperature: 150 to 240 ºF

- Reservoir pressure: > 4,000 psi

Source: Poellitzer, et al., 2009 (SPE 120991)
Project Objective

- Conduct coreflood experiments to quantify recovery potentials of continuous CO$_2$ drive at miscible conditions

- Apply X-ray Computed Tomography (CT) technique to visualize fluid flow at core level
  - Dual-energy scan at 140 keV and 80 keV

- Model the CO$_2$ injection process to reproduce experimental results
Core Sample Specification

- 1” diameter, 2” length
- Permeability (with oil): 1.8 µd
- Average porosity: 7.5%
- Pore volume: ~2 mL
Determination of Miscibility Pressure of CO\(_2\) in Dead Bakken Crude @ 38 °C (~100 °F)

Typical Bakken Reservoir Condition:
- 150 to 240 °F
- > 4,000 psi
Experimental Plan

1. Dry Core Sample
2. Inject Oil
3. Oil-Saturated Core Sample
4. Maintain P, T @ 1300psi, 38°C
5. Oil-saturated Core @ Miscible Conditions
6. Inject CO₂ at deltaP = 200psi
7. Production Starts
Experimental Set-up

- Min mass reading: 0.01g
- \( \rho_{\text{oil}} = 0.8156 \frac{g}{mL} \)
- Min V reading: \( \sim 0.012 \text{ mL} \)
Oil Recovery: 70%+ of OOIP from Bakken Core

Co-current Injection of CO₂

Recovery Factor

PV of CO₂ injected
Subtraction of Oil Images from CO$_2$ Images at High and Low Energy Levels

140 keV

- Rf = 20%
- Rf = 71%

80 keV

- Rf = 20%
- Rf = 71%
Compositional Analysis of the Bakken Crude

- Model specifications:
  - Peng-Robinson EOS with volume correction
  - Aromatics and cycloalkanes lumped into $C_{7+}$
  - Expand from $C_7$ to $C_{200}$ and lump into 5 pseudo-components
  - Limited use of non-zero binary interaction coefficients

- Regression study with PVT experimental data
  - Constant Composition
  - Differential Liberation
Comparison of Saturation Pressure at $T= 237 \, ^\circ F$

<table>
<thead>
<tr>
<th></th>
<th>Model Prediction</th>
<th>Experimental Data</th>
<th>%Error</th>
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<tbody>
<tr>
<td>Saturation Pressure</td>
<td>1991.51 psia</td>
<td>1986 psia</td>
<td>0.3</td>
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</table>
Comparison of CCE and DLE Data at T= 237 °F
Dead Oil Composition from Two-Phase Flash

<table>
<thead>
<tr>
<th>Component</th>
<th>Molar Composition of Live Oil</th>
<th>Molar Composition of Flashed Liquids</th>
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<tbody>
<tr>
<td>CO2</td>
<td>0.00260</td>
<td>0.00007</td>
</tr>
<tr>
<td>N2-CH4</td>
<td>0.25056</td>
<td>0.00196</td>
</tr>
<tr>
<td>C2H6</td>
<td>0.11868</td>
<td>0.00846</td>
</tr>
<tr>
<td>C3H8</td>
<td>0.09758</td>
<td>0.02461</td>
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<tr>
<td>IC4 - NC4</td>
<td>0.06399</td>
<td>0.04314</td>
</tr>
<tr>
<td>IC5 - NC5</td>
<td>0.04029</td>
<td>0.05275</td>
</tr>
<tr>
<td>C6</td>
<td>0.03379</td>
<td>0.05922</td>
</tr>
<tr>
<td>C7 - C10</td>
<td>0.18346</td>
<td>0.37769</td>
</tr>
<tr>
<td>C11 - C13</td>
<td>0.07872</td>
<td>0.16270</td>
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<tr>
<td>C14 - C17</td>
<td>0.06091</td>
<td>0.12592</td>
</tr>
<tr>
<td>C18 - C21</td>
<td>0.03244</td>
<td>0.06706</td>
</tr>
<tr>
<td>C22+</td>
<td>0.03696</td>
<td>0.07641</td>
</tr>
</tbody>
</table>
MCM Pressure of Dead Oil at 38 °C

- Method of Characteristics (Orr): 1069.5 psi
- Method of Multiple Mixing Cells (Ahmadi & Johns): 1175.49 psi
- Experimental Miscibility: 1200 psi

<table>
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<tr>
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<th>Method of Characteristics</th>
<th>Method of Multiple Mixing Cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Error</td>
<td>12%</td>
<td>2%</td>
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</table>
Conclusion

- CO₂ proves to be a promising EOR agent for light crudes in Bakken
  - Production starts after more than 1PV of CO₂ injected
  - At least 70% of OOIP recovered

- Impact of CO₂ injection is more pronounced at low-energy-level CT scans due to contribution of photoelectric absorption

- Existence of fractures aids the transport of CO₂

- Fluid model is capable of producing reasonable representation of PVT test results
Future Work

- More coreflood experiments to obtain good volumetric data on the effect of CO$_2$ on oil recovery

- For imaging purpose,
  - Longer exposure time
  - Use photoelectric dopants

- Flow simulation in CMG GEM to reproduce the miscible experiments
Acknowledgement

- SUPRI-A Team
- Industry Affiliates
Appendix
CT Number Comparison with PVI of CO$_2$

Changes of Average CT Number with PV of CO$_2$ Injected

- CT Number @80keV
- CT Number @140keV

PV of CO$_2$ Injected

CT Number @140keV
CT Number @80keV

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CT Number Comparison at High and Low Energy Levels

High Energy Level

CT number Comparison between CO₂ and Oil images at 140keV/120mA

Low Energy Level

CT number Comparison between CO₂ and Oil images at 80keV/120mA
Theoretical Reconstruction of CT Number Difference at
Energy Level of 140 keV

\[
CT = (1 - \phi) \cdot CT_{rock} + \phi \cdot CT_{fluid}
\]

\[
\Delta CT = \phi \cdot (CT_{fluid} (t) - CT_{fluid} (t = 0))
\]

\[
CT_{fluid} (t) = x_{CO2} CT_{CO2} + (1 - x_{CO2}) CT_{oil}
\]

\[
CT_{fluid} (t = 0) = CT_{oil}
\]

\[
x_{CO2} = \frac{R_f \rho_{CO2}}{(1-R_f) \rho_{oil} + R_f \rho_{CO2}}
\]

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<tr>
<th></th>
<th>Density g/mL</th>
<th>Pure Fluid CT Number @140keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>( CO_2 )</td>
<td>0.616</td>
<td>-335.1</td>
</tr>
<tr>
<td>Oil</td>
<td>0.785</td>
<td>-177.4</td>
</tr>
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</table>
Histogram of CT Number Differences: Experimental vs. Theoretical

Distribution of CT Number Difference at 140keV

Distribution of CT Number Difference at 140keV

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CT Number Comparison @ $\phi=7.5\%$: Theoretical vs. Experimental

CT Number Reconstruction @140keV

- CT Number Difference
- Oil Recovery, %

Theoretical
Experimental