Gas Injection in Fractured Carbonate Rocks

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Overview

➢ Background
  ✓ Matrix / fracture system in fractured reservoirs

➢ This research
  ✓ Motivation and main research question
  ✓ PVT and core properties
    ✓ Experiments and simulation
  ✓ Methodology
    ✓ Experimental set-up and procedure
  ✓ Experimental results
    ✓ Tertiary gas-oil gravity drainage in fractured porous media
  ✓ Conclusions
Background

- Unique feature of NFR:
  - Early breakthrough of injected fluid
  - More uniform fluid composition
  - Small pressure drop
  - Absence of transition zone
Analogue model
Motivation and main research question

➢ Recovering the remaining oil in the matrix after waterflooding by:

  ▪ Equilibrium gas injection in reservoir condition
    ▪ Tertiary case with wettability and Composition effect
    ▪ Re-pressurization (effect of IFT reduction)
  ▪ Non-equilibrium gas injection (CO₂ and C₁)
Fluid composition (85 °C)

<table>
<thead>
<tr>
<th>Pressure (bar)</th>
<th>Oil Phase</th>
<th>Gas phase</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$C_1$</td>
<td>$C_7$</td>
</tr>
<tr>
<td>220</td>
<td>0.7034</td>
<td>0.2966</td>
</tr>
<tr>
<td>210</td>
<td>0.6690</td>
<td>0.3310</td>
</tr>
<tr>
<td>200</td>
<td>0.6375</td>
<td>0.3625</td>
</tr>
</tbody>
</table>
Fluid properties (PVT measurements)

![Graph showing fluid properties at 85 °C]

- Pressure (bar) vs. Relative volume
- Line representing 85 °C
- Point labeled $P_b$
Fluid properties (PVT measurements)
Fluid properties (PVT measurements)
Fluid properties-EOS model

Tuned EOS Model
Non-Tuned EOS Model

Temperature (°C)
Pressure (bar)

C1, mole %
Pressure, bara

Tc
Pc
Fluid properties-IFT measurements

Pendant drop of heptane rich phase surrounded by methane rich phase

\[ \sigma = \frac{gd_e^2}{l} (\rho^L - \rho^V) \]

\[ R = \frac{d_s}{d_e} \]

\( l \): function of \( R \)

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### Table

<table>
<thead>
<tr>
<th>Pressure (bara)</th>
<th>220</th>
<th>210</th>
<th>200</th>
</tr>
</thead>
<tbody>
<tr>
<td>IFT, mN/m</td>
<td>0.15</td>
<td>0.37</td>
<td>0.68</td>
</tr>
</tbody>
</table>
IFT: Experiment vs. simulation

Simulation: Weinauge and Katz

\[ \frac{1}{\sigma^4} = \sum P_{\alpha i} (x_i \rho_l - y_i \rho_v) \]
# PVT properties

<table>
<thead>
<tr>
<th>Pressure (bara)</th>
<th>Oil density (g/cm³)</th>
<th>Gas density (g/cm³)</th>
<th>B&lt;sub&gt;o&lt;/sub&gt;</th>
<th>IFT mN/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>220</td>
<td>0.407</td>
<td>0.223</td>
<td>2.28</td>
<td>0.15</td>
</tr>
<tr>
<td>210</td>
<td>0.433</td>
<td>0.198</td>
<td>2.1</td>
<td>0.374</td>
</tr>
<tr>
<td>200</td>
<td>0.452</td>
<td>0.178</td>
<td>1.98</td>
<td>0.686</td>
</tr>
</tbody>
</table>
## Properties of porous media

<table>
<thead>
<tr>
<th>Properties</th>
<th>Chalk (water wet)</th>
<th>Limestone (mix wet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permeability (mD)</td>
<td>5.2</td>
<td>14.0</td>
</tr>
<tr>
<td>Porosity %</td>
<td>44.0</td>
<td>23.0</td>
</tr>
<tr>
<td>Length (cm)</td>
<td>19.6</td>
<td>18.0-19.0</td>
</tr>
<tr>
<td>Pore Volume (cm³)</td>
<td>98-99</td>
<td>47.0-50.0</td>
</tr>
<tr>
<td>$H_c @ 0.37$ mN/m</td>
<td>3.48 cm</td>
<td>4.8 cm</td>
</tr>
<tr>
<td>$H_c @ 0.15$ mN/m</td>
<td>1.41 cm</td>
<td>1.97 cm</td>
</tr>
</tbody>
</table>
Properties of porous media

Moldic and vuggy porosity (blue)
Sparitic calcite cement (white)

Sample No. | $S_{wi}$ % | $S_{or}$ % | $S_{w} @ k_{rw} = k_{ro}$
--- | --- | --- | ---
1 | 15.6 | 24.3 | 33
2 | 25.8 | 31.7 | 46
3 | 18.7 | 32.4 | 34
4 | 18.9 | 32.7 | 40
5 | 20.4 | 31.8 | 39

26-Oct-15
Summary of experiments

<table>
<thead>
<tr>
<th>Exp. No</th>
<th>Water injection</th>
<th>Equilibrium gas injection at 210 bar (IFT=0.37 mN/m)</th>
<th>Equilibrium gas injection at 220 bar (IFT=0.15 mN/m)</th>
<th>CO₂ injection</th>
<th>C₁ injection</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-Chalk (water wet)</td>
<td>✓.</td>
<td>✓.</td>
<td>✓.</td>
<td>✓.</td>
<td>----</td>
</tr>
<tr>
<td>2-Chalk (water wet)</td>
<td>✓.</td>
<td>✓.</td>
<td>✓.</td>
<td>----</td>
<td>✓.</td>
</tr>
<tr>
<td>3-Limestone (mix wet)</td>
<td>✓.</td>
<td>✓.</td>
<td>✓.</td>
<td>✓.</td>
<td>----</td>
</tr>
<tr>
<td>4-Limestone (mix wet)</td>
<td>✓.</td>
<td>✓.</td>
<td>✓.</td>
<td>----</td>
<td>✓.</td>
</tr>
</tbody>
</table>
Methodology: Experimental Set-up

Methodology in gas injection experiment:

- Sealing the fracture
  - Special alloy (woods metal)
    - Melting point = 67 °C
- Re-opening the fracture
Methodology: Experimental Set-up

1- Quizix pump.
2,3- Isolated cells
4- Isolated constant temperature tube
5- Pressure transmitter
6- Steel tube containing matrix and fracture.
7- By-pass system
8- Sealing material accumulator
9- Back pressure regulator
10- Condenser
11- Seperator
12- Gas wet test meter
13- Gas chromatograph
CO$_2$ injection in water-wet sample

- Equ. Gas, 210 bar
  - IFT=0.37 mN/m
  - Water injection
  - 13% recovery

- Equ. Gas, 220 bar
  - IFT=0.15 mN/m
  - CO$_2$ injection
  - 6% recovery

- CO$_2$ injection
C₁ injection in water-wet sample

Recovery, fraction of OOIP

Time (day)

Water injection

Start of Equ. Gas, 210 bar

Re-pressurization

Equ. Gas, 220 bar

C₁ injection

16%

5%

4%
CO$_2$ vs. C$_1$

![Graph showing recovery fractions of OOIP for CO$_2$ and C$_1$ injections over time.](image-url)
CO$_2$ injection in mix-wet sample

- Water Injection
- Eq. Gas, 210 bar
  - 41% recovery
- Re-pressurization
  - Eq. Gas, 220 bar
  - 9% increase
- CO$_2$ Injection
  - 15% increase
C\textsubscript{1} injection in mix-wet sample

Recovery, fraction of OOIP

- Water Injection
- Eq. Gas, 210 bar: 32%
- Re-pressurization
  - Eq. Gas, 220 bar: 16%
- C\textsubscript{1} Injection
  - 12%

Time (day)

0 1 2 3 4 5 6
CO₂ vs. C₁

![Graph showing CO₂ vs. C₁ recovery over time]
Summary of experimental results

<table>
<thead>
<tr>
<th>Exp. No</th>
<th>Recovery Mechanism</th>
<th>Wettability</th>
<th>Water injection R.F %</th>
<th>Equilibrium gas injection R.F %</th>
<th>Non-equilibrium gas injection R.F %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Tertiary (water injection +GOGD+CO₂)</td>
<td>Water-wet</td>
<td>55</td>
<td>19</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>Tertiary (water injection +GOGD+C₁)</td>
<td>Water-wet</td>
<td>60</td>
<td>21</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>Tertiary (water injection +GOGD+CO₂)</td>
<td>Mix-wet</td>
<td>8</td>
<td>50</td>
<td>15</td>
</tr>
<tr>
<td>4</td>
<td>Tertiary (water injection +GOGD+C₁)</td>
<td>Mix-wet</td>
<td>8</td>
<td>48</td>
<td>12</td>
</tr>
</tbody>
</table>
Conclusion

1- Gas-oil gravity drainage at low interfacial tension was found to be a very effective oil recovery method from mix-wet and water-wet fractured media at both secondary and tertiary injection.

2- Additional oil recovery could be obtained by injection of non-equilibrium gas, where diffusion and gravity drainage are the key factors for increased oil recovery.

3- Injection of lean gas such as $C_1$ can also improve the oil recovery significantly.

4- $CO_2$ injection is more efficient compared to $C_1$ injection in fractured carbonate rock.
References:


- A.M. Saidi,. “Reservoir Engineering of Fractured Reservoirs”. Total 1987

Thank you!

*Life can only be understood backwards, but has to be lived forwards*