EVALUATION AND OPTIMIZATION OF GAS ASSISTED GRAVITY DRAINAGE PROCESS

Teerawat Vaccharasiritham
Suwat Athichanagorn

Chulalongkorn University
Introduction

- **Gravity overriding, viscous instability** of injection front and early breakthrough are common problem of gas injection, due to the unfavorable mobility ratio.
- **Gas assisted gravity drainage (GAGD)** in dipping reservoir is one of the most efficient methods in both secondary and tertiary modes.
- Gravity segregation helps to maintain pressure and the stability of gas flood front and also improves volumetric displacement efficiency.
Objectives

1. To investigate the effects of design parameters and determine appropriate production strategy for dipping reservoir
   - Oil production rate
   - Gas injection rate
   - Well pattern

2. To determine the sensitivity of reservoir parameters
   - Relative permeability correlation
   - Vertical to horizontal permeability ratio
   - Relative permeability to oil and gas.
Fractional Flow Equation

Gravity term

\[ f_g = \frac{1 - k_{kr} \Delta \rho \sin \alpha / q \mu}{1 + k_{rg} \mu_o / k_{ro} \mu_g} \]

(Effect of Capillary force is neglected)

Where

\( \Delta \rho = \) density difference, \( \rho_o - \rho_g \)
\( \alpha = \) dip angle (positive down dip)

Gas injection

![Graph showing the effect of gravity term on fractional flow](image)

With Gravity Term

No Gravity Term
Reservoir Model

- ECLISPE black-oil reservoir simulator (E100) is used in this study
- Undersaturated homogenous reservoir with 15, 30 and 60 degree dip angles
- The maximum simulation time is **100 years**
- The concession period is assumed to be **30 years**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity</td>
<td>15.09</td>
<td>%</td>
</tr>
<tr>
<td>Horizontal permeability</td>
<td>32.529</td>
<td>mD</td>
</tr>
<tr>
<td>Vertical permeability</td>
<td>3.2529</td>
<td>mD</td>
</tr>
<tr>
<td>Top depth</td>
<td>5000</td>
<td>ft</td>
</tr>
</tbody>
</table>

**Production well constraints**
- Cut off oil production rate (STB/D) 100
- Minimum bottomhole pressure (psia) 500

**Injection well constraint**
- Maximum bottomhole pressure (psia) 3300
Results and Discussion
Natural depletion (Base Case)

- Reservoir pressure declines rapidly
- Oil production declines due to the flow of gas that comes out of oil
- Oil recovery factor increases with higher dip angle

Free gas starts to flow into the well

Reservoir pressure drops dramatically
Gas Assisted Gravity Drainage (GAGD)

Benefit of GAGD
- Maintain the reservoir pressure
- Extend the plateau period
- Shorter production time
- Reduce flow of gas near the well bore
Effect of oil production and gas injection rate

Two scenarios are used to study the effect of oil production rate and gas injection rate:

- Vary oil production (gas injection rate based on oil production rate)
- Vary gas Injection rate with fixed oil production rate
Effect of oil production and gas injection rate

For dip angle of 15 degrees

- $q_{o,prod} = 1000 \text{ STB/D}, q_{g,inj} = 1100 \text{ MSCF/D}$
- $q_{o,prod} = 2000 \text{ STB/D}, q_{g,inj} = 2300 \text{ MSCF/D}$
- $q_{o,prod} = 3000 \text{ STB/D}, q_{g,inj} = 3500 \text{ MSCF/D}$
- $q_{o,prod} = 4000 \text{ STB/D}, q_{g,inj} = 4700 \text{ MSCF/D}$

Production profile

- The higher production rate, the earlier gas breaks through
Oil saturation distribution at 30 years

(a) Oil production rate: 1000 STB/D
(b) Oil production rate: 2000 STB/D
(c) Oil production rate: 3000 STB/D
(d) Oil production rate: 4000 STB/D
At the end of 30 years, production rates of 2000, 3000, and 4000 STB/D give comparatively high recovery factors. Production rates of 2000, 3000, and 4000 STB/D cause gas breakthrough within 30 years.
Effect of oil production and gas injection rate

For dip angle of 15 degrees

<table>
<thead>
<tr>
<th>CASE</th>
<th>Oil production rate (STB/D)</th>
<th>Gas injection rate (MSCF/D)</th>
<th>RF (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2000</td>
<td>2300</td>
<td>56.28</td>
</tr>
<tr>
<td>2</td>
<td>2000</td>
<td>3500</td>
<td>59.14</td>
</tr>
<tr>
<td>3</td>
<td>2000</td>
<td>4700</td>
<td>59.80</td>
</tr>
<tr>
<td>4</td>
<td>3000</td>
<td>3500</td>
<td>57.29</td>
</tr>
<tr>
<td>5</td>
<td>3000</td>
<td>4700</td>
<td>60.35</td>
</tr>
<tr>
<td>6</td>
<td>3000</td>
<td>6000</td>
<td>61.40</td>
</tr>
<tr>
<td>7</td>
<td>4000</td>
<td>4700</td>
<td>58.89</td>
</tr>
<tr>
<td>8</td>
<td>4000</td>
<td>6000</td>
<td>61.53</td>
</tr>
<tr>
<td>9</td>
<td>8000</td>
<td>8000</td>
<td>63.14</td>
</tr>
</tbody>
</table>

- **Increasing injection rate** provides **higher oil recovery**
- **Small increase** in oil recovery when the injection rate is limited by the fracture pressure

The most appropriate design parameter is:
- Oil production rate: 4000 STB/D
- Gas injection rate: 6000 MSCF/D
Effect of oil production and gas injection rate

- For dip angle of 30 degrees
  the most appropriate design parameter is
  - oil production rate : 3000 STB/D
  - Gas injection rate : 4900 MSCF/D

- For dip angle of 60 degrees
  the most appropriate design parameter is
  - oil production rate : 3000 STB/D
  - Gas injection rate : 5400 MSCF/D
Effect of well pattern

Well pattern 1

Well pattern 2

Well pattern 3

Well pattern 4
Results of well pattern

- For dip angle of 15, 30, 60 degrees

- Well pattern 1 (Horizon well) provides the highest oil recovery at 30 years (0.61-0.69) because
  - Deeper location of producers provides longer and more stable oil production
  - High gas production in early time for well pattern 3 and 4 results in lower oil recovery
Effect of relative permeability correlations

At the end of production time

<table>
<thead>
<tr>
<th>Dip angle</th>
<th>Model</th>
<th>Production time (years)</th>
<th>Cumulative oil production (MMSTB)</th>
<th>Cumulative gas production (BSCF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>ECLIPSE default</td>
<td>72.25</td>
<td>24.88</td>
<td>167.75</td>
</tr>
<tr>
<td></td>
<td>Stone 1</td>
<td>72.58</td>
<td>24.92</td>
<td>168.50</td>
</tr>
<tr>
<td></td>
<td>Stone 2</td>
<td>69.09</td>
<td>24.62</td>
<td>160.76</td>
</tr>
<tr>
<td>30</td>
<td>ECLIPSE default</td>
<td>49.67</td>
<td>25.30</td>
<td>96.90</td>
</tr>
<tr>
<td></td>
<td>ECLIPSE</td>
<td>49.83</td>
<td>25.31</td>
<td>97.23</td>
</tr>
<tr>
<td></td>
<td>Stone 2</td>
<td>44.42</td>
<td>24.91</td>
<td>87.30</td>
</tr>
<tr>
<td>60</td>
<td>ECLIPSE default</td>
<td>51.25</td>
<td>25.91</td>
<td>101.43</td>
</tr>
<tr>
<td></td>
<td>Stone 1</td>
<td>51.58</td>
<td>25.96</td>
<td>102.12</td>
</tr>
<tr>
<td></td>
<td>Stone 2</td>
<td>42.42</td>
<td>25.41</td>
<td>83.32</td>
</tr>
</tbody>
</table>

- Insignificant difference in oil production among these correlations for dip angle of 15, 30 and 60 degrees (around 1.2 to 2.2 %).
- Stone 1 gives slightly higher oil production than other correlations.
- Stone 2 model yields shorter production time.
Effect of vertical to horizontal permeability

In small dip angle (15 degrees)
- Effect of gravity < capillary force
- Gas tends to bypass oil and breakthrough earlier when increasing $k_v/k_h$
- Lower RF when increasing $k_v/k_h$

<table>
<thead>
<tr>
<th>Case</th>
<th>Vertical to horizontal permeability ratio</th>
<th>Vertical Permeability (md)</th>
<th>Horizontal Permeability (md)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.01</td>
<td><strong>0.32529</strong></td>
<td>32.529</td>
</tr>
<tr>
<td>2</td>
<td>0.1</td>
<td><strong>3.2529</strong></td>
<td>32.529</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td><strong>32.529</strong></td>
<td>32.529</td>
</tr>
</tbody>
</table>

At 30 years

In high dip angle (30 and 60 degrees)
- The effect of gravity > capillary force
- Gas breakthrough occur later when $k_v/k_h$ is higher
- Higher RF when increasing $k_v/k_h$
Effect of relative permeability to oil and gas

- Residual oil saturation ($S_{org}$) is used as a study parameter to change $k_{rog}$
  - 0.05
  - 0.10
  - 0.15

- Increasing $S_{org}$ causes
  - $K_{rog}$ shifts to the left
  - Lower oil recovery factor
  - Difference in oil recovery factor obtained from the sets of $S_{org}$ is up to 9.41%

At 30 years
Conclusion

- GAGD considerably increases oil production comparing to that of natural depletion.

- Reservoir dip angle affects the oil recovery. An increase in dip angle enables gravity effect to improve the stability of flood front and increase gas sweep efficiency.

- Oil production rate is a key parameter in GAGD process.
  - Very low production rate results in a stable gas flood front and high oil recovery. However, it takes impractically long production time.
  - Higher production rate accelerates oil production, but it also causes early gas breakthrough, resulting in poor sweep efficiency.

- When production rate is fixed, increasing gas injection rate provides higher oil recovery.
  - Once gas injection rate is so high that the injector BHP exceeds the fracture pressure, oil recovery is insignificantly increased.
Conclusion

- In dipping reservoirs, in order to delay gas breakthrough and maximize volumetric sweep efficiency.
  - gas injector should be located at the most updip location
  - production well should be placed at the most downdip location

- Increasing vertical to horizontal permeability ratio significantly increases oil recovery, improves displacement efficiency.

- Insignificant difference in oil production among three study correlations for every dip angle.

- Decrease in residual oil saturation in gas-oil system results in higher oil recovery and longer production time.
Q&A
Effect of relative permeability correlations

- Relative permeability correlation
- ECLIPSE default model
- Stone 1 model
- Stone 2 model

Comparison of cumulative oil production at different angles:
- 30 degrees
- 15 degrees
- 60 degrees
Effect of relative permeability correlations

- Relative permeability correlation
  - ECLIPSE default model
  - Stone 1 model
  - Stone 2 model

Graphs showing the effect of different models on gas-oil ratio over time for different inclinations:

- **15 degrees**
  - ECLIPSE default
  - Stone 1
  - Stone 2

- **30 degrees**
  - ECLIPSE default
  - Stone 1
  - Stone 2

- **60 degrees**
  - ECLIPSE default
  - Stone 1
  - Stone 2
Reservoir Model
Results of well pattern

- Production profile for dip angle of 15 degrees

- Oil production decline faster in well pattern 3 and 4 due to gas production at early time

- The deeper location of producer, the longer plateau period and the later gas breaks through
Effect of relative permeability to oil and gas

- Residual oil saturation ($S_{\text{org}}$) is used as a study parameter to determine the effect of different relative permeability to oil and gas.
- Three values of $S_{\text{org}}$ are used: 0.05, 0.10, 0.15.

From Corey Correlation in oil-gas system:

$$k_{ro} = \left(\frac{S_g - S_{wi} - S_{org}}{1 - S_{wi} - S_{org}}\right)^{N_o}$$

$$k_{rg} = \left(\frac{S_g - S_{gc}}{1 - S_{wi} - S_{org} - S_{gc}}\right)^{N_g}$$
Effect of oil production and gas injection rate

For dip angle of 60 degrees

- Increasing injection rate provides higher oil recovery
- Once injection rate is limited by fracture pressure, increasing gas injection rate results in slight increase in oil recovery

<table>
<thead>
<tr>
<th>CASE</th>
<th>Oil production rate (STB/D)</th>
<th>Gas injection rate (MSCF/D)</th>
<th>At 30 years</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>RF (%)</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>3700</td>
<td>64.57</td>
</tr>
<tr>
<td>2</td>
<td>3000</td>
<td>4900</td>
<td>67.51</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>6500</td>
<td>67.93</td>
</tr>
<tr>
<td>4</td>
<td>4000</td>
<td>4900</td>
<td>64.05</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>6500</td>
<td>66.77</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>8500</td>
<td>67.32</td>
</tr>
</tbody>
</table>

**Case 2** is the most appropriate design parameter for 60-degree dip angle