THE EFFECT OF FOAM STABILITY IN CO$_2$-FOAM FLOODING

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- CO₂ can perform both miscible and immiscible conditions.
- Mobility of CO₂ is much higher than crude oil.
- Gravity overriding and viscous fingering occur.
- Finally, it leads to the early gas breakthrough.

- Foam was used to control the mobility of gas phase and improve the sweep efficiency.
- Foam create smoother and more stable flood front.
- Main mechanism for oil recovery comes from CO₂ gas and displacement by foam.
- Foam stability is a parameter that indicate foam’s strength
Objectives

• To study the effects of interest parameters including wettability, hydrocarbon component and number of slug on effectiveness of CO$_2$-foam flooding process.

• To determine the optimal foam stability in CO$_2$-foam flooding process.
**Methodology**

1. Construct a reservoir model

2. Run CO₂ base case

3. Perform CO₂ foam flooding process

4. Vary the formation wettability

5. Vary hydrocarbon composition

6. Vary the injection slug

7. Analyze and summarize the obtained results

### Parameters

**Wettability**
- Moderately water-wet
- Neutral-wet
- Moderately oil-wet
- Strongly oil-wet

**Intermediate**
- ↑ Intermediate comp. 10%
- ↑ Intermediate comp. 20%
- ↓ Intermediate comp. 10%
- ↓ Intermediate comp. 20%

**CO₂ foam slug**
- Double-slug (0.2 PV)
- Triple-slug (0.13PV)
The simulator STARS will be used to evaluate the performance of CO$_2$-foam flooding in this study.

The studied reservoir model is created as Cartesian grid and represents homogeneous reservoir.

### Property | Value
--- | ---
Top reservoir depth, feet | 6,000
Grid block number | $30 \times 15 \times 20$
Grid size, feet | $100 \times 100 \times 10$
Thickness, feet | 200
Porosity | 0.25
Initial water saturation | 0.28
Horizontal permeability, mD | 220
Vertical permeability, mD | 22
Reservoir temperature, °F | 198
Reservoir pressure, psia | 2,775

### Component | Mole fraction
--- | ---
Carbon dioxide (CO$_2$) | 0.0091
Nitrogen (N$_2$) | 0.0006
Methane (C$_1$) | 0.3383
Ethane (C$_2$) | 0.0904
Propane (C$_3$) | 0.0799
Isobutane (i-C$_4$) | 0.0197
Normal butane (n-C$_4$) | 0.0469
Isopentane (i-C$_5$) | 0.036
Normal pentane (n-C$_5$) | 0.0178
Hexane (C$_6$) | 0.0501
Heptane plus (C$_{7+}$) | 0.3112
Wells and recurrent section

- The production well is located at the edge of the reservoir, while the injection well is at the edge on another side of the model.

### Constraints of the production well

<table>
<thead>
<tr>
<th>Constraint</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface oil rate, BBL/D</td>
<td>2,000</td>
</tr>
<tr>
<td>Surface water rate, BBL/D</td>
<td>2,000</td>
</tr>
<tr>
<td>Surface gas rate, MMSCF/D</td>
<td>10</td>
</tr>
<tr>
<td>Cut-off oil production rate, BBL/D</td>
<td>100</td>
</tr>
<tr>
<td>Water cut, %</td>
<td>95</td>
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</tbody>
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SIMULATION RESULTS AND DISCUSSION
**CO₂ flooding Base Case**

- Fluid injection schedule is divided in two periods, 0.4 PV of CO₂ and 0.4 PV of water

- The ultimate oil recovery factor is about 42.6%

**Oil, water and gas production rates**

- Cum inj CO₂ reached 0.4 PV, water started injection
- Production rates dropped due to the decreasing of reservoir pressure
- Oil rate increased again because of the sweeping of chasing water
- Oil rate dropped due to water breakthrough
**CO$_2$-foam flooding base case**

- The injection schemes are kept to be similar to CO$_2$ flooding base case.
- In this study, foam stability are varied from 20 days, 40 days, 80 days, 160 days, and 320 days.

**Oil production rates**

- Water breakthrough came from the aqueous phase of foam. (when foam breaks and gas phase and aqueous phase flow separately)

**Water production rates**

- From oil production rate and water production rate, the effect of foam stability are not noticeable much.
The summary of oil production, water production, gas production and oil recovery factor

<table>
<thead>
<tr>
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<th>CO$_2$ flooding</th>
<th>CO$_2$-Foam flooding</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>FS 20 days</td>
<td>FS 40 days</td>
</tr>
<tr>
<td>Water 0.4 pore volume, day</td>
<td>6,350</td>
<td>9,796</td>
</tr>
<tr>
<td>Cumulative oil production (MMBBL)</td>
<td>7.91</td>
<td>9.94</td>
</tr>
<tr>
<td>Cumulative water production, (MMBBL)</td>
<td>0.98</td>
<td>11.00</td>
</tr>
<tr>
<td>Cumulative gas production (BSCF)</td>
<td>30.52</td>
<td>19.37</td>
</tr>
<tr>
<td>Oil recovery factor, %</td>
<td>42.62</td>
<td>55.48</td>
</tr>
</tbody>
</table>

This result could be from continuous injecting slug of CO$_2$-foam, so an effect of foam stability cannot be seen obviously.
CO$_2$-foam flooding base case

- Since foam can create the smoother flood front compared to the case of CO$_2$ flooding.

- The CO$_2$-foam flooding provides the higher ultimate oil recovery factor than CO$_2$ flooding about 13%
Effect of varied parameters on CO$_2$-foam flooding
The effect of wetting condition of reservoir rock

Summary of the effects of wettability

- CO$_2$-foam flooding is suitable for a reservoir that its wettability is in the range of neutral-wet to strongly water-wet.
- For oil-wet formation, solely CO$_2$ flooding is preferable.
The effect of hydrocarbon compound

Increasing intermediate portion 20%

- Oil production rate
  - Oil declines due to foam breakthroughs.

- Water production rate
  - More intermediate part is vaporized \( \Rightarrow S_o \) is reduced \( \Rightarrow K_{rw} \) is increased \( \Rightarrow \) foam flows faster

- Gas production rate

- CO\textsubscript{2} foam breakthroughs
The effect of hydrocarbon compound

Decreasing intermediate portion 20%

- Oil production rate
  - Oil declines due to foam breakthroughs.

- Gas production rate
  - Gas from arrival of foam.

- Water production rate
  - Water from arrival of foam.
  - Water from chasing water B.T.

- CO₂ foam breakthroughs
  - Foam does not break during flowing in the reservoir because foam tends to be more stable in heavier oil.
The effect of injection slug

- Divide foam injection from 0.4 pore volume into two slugs of 0.2 pore volume and three slugs of 0.133 pore volume. Each slug is alternated with chasing water slugs.

- The injecting CO$_2$ foam can maintain pressure better than the injecting water.
- Pressure in latter stage is more important because high pressure leads to maintaining of produced water after water breakthrough.
- The production in the cases of multi-slug were terminated because of water cut reach 95%.
Conclusion

**CO₂-foam flooding**

- CO₂-foam flooding cases have ability to enhance hydrocarbon recovery.
- Foam provides smoother flood front.
- Water breakthrough in CO₂-foam flooding causes the reduction of oil production rate

**Foam stability**

- Variation of foam stability does not significantly impact on production performance of CO₂-foam flooding.
- The difference of oil recovery factors by varying foam stability is smaller than 2%.
- It could be possible that there are other parameters involve, so effects of foam stability cannot be clearly seen.
The influences of wettability on effectiveness and performance of CO$_2$-foam flooding

For CO$_2$-foam flooding, the suitable formation wettability should be in the range of neutral-wet to strongly water-wet

CO$_2$ flooding provides better performance when perform in the formation that wettability ranging from oil-wet or strongly oil-wet condition
The influences of intermediate compound in hydrocarbon on effectiveness and performance of CO$_2$-foam flooding

Intermediate portion in liquid hydrocarbon.

- Implementation of CO$_2$-foam flooding with light oil containing high portion of intermediate (C$_2$-C$_6$) results in high velocity of injected foam.
- Intermediate compound tends to destabilize foam more than oil containing higher portion of heavy compound (C$_7$+).
Conclusion

- The influences of slug injection on effectiveness and performance of CO$_2$-foam flooding

Dividing CO$_2$-foam slug into multi-slugs can maintain pressure better than single-slug. So, when water breakthrough occurs, oil production is terminated because of 95% water cut.

In this study, single-slug mode of CO$_2$-foam provides the best outcome.
THANK YOU
The effect of wetting condition of reservoir rock

• Wetting conditions that are varied from an original value in a direction to more oil-wet.

1. Reducing irreducible water saturation
2. Increasing the relative permeability to water at residual oil saturation
3. Decreasing of crossover saturation

More oil-wet

• Vary the wettability condition 4 cases
  1. Moderately water-wet
  2. Neutral wet
  3. Moderately oil- wet
  4. Strongly oil-wet
**CO₂ flooding Base Case**

- **Miscibility effect**

**Orange zone**: Initial oil density

**Red zone**: The left oil that cannot be vaporized by CO₂

**Blue zone**: no oil left, pores are all occupied by CO₂

**Blue zone**: Initial gas density

**Green Zone**: gases which have lower mass density than CO₂ (CH₄)

**Yellow & orange zone**: mixing zone between CO₂ and vaporized intermediate

**Red zone**: zone of CO₂
Oil mass density changes similarly as in the case of CO₂ flooding, but due to amount of CO₂ released from foam is not as much as the case of CO₂ flooding, area of miscibility is much smaller.