CO$_2$-Foam-Gel Treatments for Improved Conformance Control & Oil Recovery

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Outline

• Introduction to Foam-Gel Concept

• Summary: Development & Field Application of CO$_2$-Foam-Gel system for Chevron’s Rangely reservoir (naturally fractured sandstone)

• Discussion: Potential for broader application of foam-gel technology in other heterogeneous & fractured reservoirs
Project Team & References

• SLB-Chevron collaboration 1996-2000:
  • Research Project Team:
    • SLB: T.L. Hughes, S.N. Davies, A.D. Wilson
    • Chevron: F. Friedmann, G. Hild
  • Other key contributions:
    • SLB: M. Parris (SLB): CO$_2$-Foam injectivity trials
    • Chevron: M.E. Smith, D. Johnson, R. Wackowski:
      Well/pattern selection, treatment design/execution

• Published References & granted US Patent
Key Components of Project

• Focus: CO₂-Foam-Gel for Rangely reservoir conditions
• Lab-based development: CO₂-Foam-Gel chemistry/formulation
  • SCR lab, Cambridge, UK; Chevron lab, La Habra, CA
  • Optimisation of key fluid system parameters:
    • vol% CO₂; polymer chemistry, dosage & quality control; surfactant chemistry & concentration; delayed gelation system & performance; flow resistance gelled foam (lab & reservoir conditions)
• Rangely Field treatments
  • Well/Pattern Selection
  • Treatment Design/Execution:
    • Treatment Volume; CO₂-Foam Delivery Method & Injectivity; Delayed Gelation Design & Control; Methods to determine changes in vertical/areal conformance & to calculate incremental oil recovery
  • Three CO₂-Foam-Gel injector well treatments pumped – each 35000-45000bbl
Introduction: Foam-Gel Concept

- Problem type:
  - poor utilisation of injected gas due to poor sweep efficiency (high k paths, e.g. fractures)

- Foam-gel
  - Large volume, cost-effective
  - behaves as a foam during injection (enters gas thief zones)
  - after placement, liquid phase gels for enhanced flow resistance & long-term stability
Rangely Reservoir Conditions

• Rangely reservoir on WAG injection (CO$_2$) since 1986
• Naturally fractured sst
  • 5500-6500ft, T=160°F
  • Matrix perm 0.1-200mD
  • Fracture perm 10-50D
  • P(CO$_2$)>2600psi (miscible)
  • $\rightarrow$ low pH conditions

$\rightarrow$ Research Challenge in CO$_2$-Foam-Gel Development:
• Delayed gelation of aqueous phase under low pH conditions
Delayed Gelation System & Performance

- **Gelation Delay Mechanisms**
  - PHPA polymer with initially low degree of hydrolysis (DH 0.5-1%) → DH increases under reservoir conditions
  - Cr acetate crosslinking delayed by addition of sodium lactate

- **Key Performance Factors**
  - Some foaming surfactants interfere with or even inhibit crosslinking
  - Many surfactants screened for (1) foaming performance & (2) influence on delayed gelation system
  - Surfactant Selection Critical
  - Delayed bicarbonate buffer (urea) to ensure ionisation of PHPA polymer for subsequent crosslinking
  - In all 3 field treatments, concentration of gelation delay agent (lactate) down- ramped to ensure similar timing of gelation of first and last pumped foam
  - Capped with gel only treatment at wellbore for maximum strength
Delayed Gelation System – pH Effect

6.3 active g/L PHPA DH = 0.5-1%, 130 ppm Cr(III) as acetate
0.5 wt% surfactant, Rangely brine, T = 160 F
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0.5 wt% surfactant, Rangely brine, T = 160 F

Gel Strength Code
- Molar Lact/Acet = 1/1
- Molar Lact/Acet = 1.5/1
- Molar Lact/Acet = 2.5/1
- No Lactate
Flow Resistance: Gel, Foam, Gelled Foam

$T = 160 \, ^{\circ}\text{F}; \, P = 1,900 \, \text{psi}$

Lab-based Studies
16D sandpack
Foam & Gelled Foam contain 80vol% CO$_2$ + 20vol% liquid (aq) phase
# Rangely Field Treatments

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Volume</th>
<th>Pre-Treatment</th>
<th>Post-Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>I (Nov/96)</td>
<td>36400 bbl</td>
<td>-126</td>
<td>+36</td>
</tr>
<tr>
<td>II (Sep/97)</td>
<td>43500 bbl</td>
<td>-80</td>
<td>+56</td>
</tr>
<tr>
<td>III (Nov/97)</td>
<td>44700 bbl</td>
<td>-65</td>
<td>+45</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Foam Injection rate</th>
<th>2 bbl/min</th>
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</thead>
</table>

**Treatment I**
- LNH A17X
- ACMC 11
- EM 90X
- LNH A9X
- EM 11
- LNH A8
- EM 60X

**Treatment II**
- Gray 15
- Gray 22X
- Gray 10
- Gray 12
- ASOA4X
- ACMC 4
- ACMC 75X
- ACMC 70X

**Treatment III**
- ACMC 21
- ACMC 71X
- ACMC 9
# Rangely Field Treatments

<table>
<thead>
<tr>
<th>80 vol% Foam-gel Treatment</th>
<th>Treatment Volume, bbl</th>
<th>Pattern Oil Rate Pre-treatment, BOPD/year</th>
<th>Pattern Oil Rate Post-treatment, BOPD/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>I (Nov/96)</td>
<td>36,400</td>
<td>-126</td>
<td>+36</td>
</tr>
<tr>
<td>II (Sep/97)</td>
<td>43,500</td>
<td>-80</td>
<td>+56</td>
</tr>
<tr>
<td>III (Nov/97)</td>
<td>44,700</td>
<td>-65</td>
<td>+45</td>
</tr>
</tbody>
</table>

Foam Injection rate 2 bbl/min
Treatment I: Changes in Vertical Conformance

- Pre-treatment
  - Alternating CO\textsubscript{2} and water injection entering DIFFERENT zones
  - CO\textsubscript{2} mainly entering top zone

- CO\textsubscript{2}-Foam-Gel treatment
  - Entered both top (6040-6080ft) and bottom (6400-6520ft) zones
  - Foam ensures CO-INJECTION 80vol%CO\textsubscript{2}/20vol%water

- Post-treatment
  - CO\textsubscript{2}-Foam-Gel treatment results in very effective DIVERSION
  - Alternating CO\textsubscript{2} and water now enter NEW (previously bypassed) zone (6120-6260ft) and top of lower zone
  - Also, significant increase in CO\textsubscript{2} breakthrough times to producers

**CO\textsubscript{2} and H\textsubscript{2}O injection profiles**

**Pre-treatment**
- CO\textsubscript{2} Sep/96
- H\textsubscript{2}O Apr/96

**Post-treatment**
- CO\textsubscript{2} 24Mar/97
- H\textsubscript{2}O 07Jan/97

**Depth (feet)**

**Volume % injectant entering zones**
Treatment I: Changes in Pattern Oil Production

-126 BOPD / yr

Foam-Gel Treatment I

+ 36 BOPD / yr

Incremental Oil recovery

Pattern Oil Rate (BOPD)

Treatment I: Changes in Oil Production per well

Treatment I: Oil Production EM60X, EM90X

EMERALD 60X
EMERALD 90X
Foam gel

Treatment I: GOR EM60X, EM90X

EMERALD 60X
EMERALD 90X
Foam gel

EM 90X, 60X:
• higher oil rate
• lower GOR
ACMC 11, EM 11:
• higher oil rate
LNH A17X, A8:
• no change in oil rate
Broader application of foam-gel approach (I)

- First step: establish problem type
  - reservoir characteristics & production history
  - where gas now injected for sweep / pressure maintenance, is sweep efficiency limited by preferential flow through the high k zones / fracture network?
  - estimate suitable foam-gel treatment volume – estimate high k zone / fracture network volume

- Pre-gel foam must be injectable into target zone
  - permeability, properties of high k zone / fracture network?
  - permeability contrast target zone / matrix?
• Optimum vol% gas in foam / gelled foam?

• pH, ionic composition of liquid phase in equilibrium with gas (CO$_2$) under reservoir conditions?
  • Select appropriate foaming surfactant (temperature)
  • Select polymer & controllable delayed gelation chemistry

• Consider interaction of foam-gel components with reservoir during placement, i.e. allow for adsorption of surfactant, crosslinker, delay agents
**Summary & Conclusions**

**CO₂-foam-gel field treatments (SLB-Chevron)**

- Very encouraging results - improved conformance and significant incremental oil recovery
- Cost CO₂-foam-gel is 40-50% of polymer gel (equiv. vol.)
- Critical benefit of Foam-gel approach is PLACEMENT

**Critical steps in considering Foam-Gel approach**

- Problem type
- High k / fracture properties, permeability contrast
- Customise chemistry to specific reservoir conditions:
  - vol% gas, surfactant, polymer, gel delay chemistry
- Complement green CO₂ Sequestration to produce more oil
Thank you