CO₂ EOR Basics: Terms and Concepts

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www.sequestration.org
Outline

• General Oil Recovery
• CO$_2$ Displacement Process
• Field Injection Options
• Summary
General Oil Recovery: Definition

- Fraction of oil produced compared to original oil in place
- Oil Recovery ($E$) is the product of *Microscopic* ($E_D$) and *Macroscopic* ($E_V$) displacement efficiency

$$E = E_D E_V$$
General Oil Recovery: Microscopic Displacement

- Microscopic Displacement
  - Initial oil saturation
  - Residual oil saturation

- $E_D$
- Process dependent
- Differs for
  - Water
  - $CO_2$
  - Chemical
Background: Oil Recovery

- Microscopic Displacement

**Diagram:**
- Matrix
- Pore Body
- Water
- Continuous Oil Phase
- Discontinuous Oil Phase

**Labels:**
- Oil
- Water
- Matrix
- Pore Throat
General Oil Recovery: Microscopic Displacement
General Oil Recovery: Macroscopic Displacement

• Macroscopic Displacement
  – Areal sweep efficiency \( (E_A) \)
  – Vertical sweep efficiency \( (E_I) \)

• \( E_V = E_A \cdot E_I \)

• \( E_V \)
  – Process dependent
  – Geologic heterogeneity
  – Injector/producer
    – Pattern
    – Spacing
General Oil Recovery: Macroscopic Displacement

• Areal Sweep Efficiency

(Plan View)
General Oil Recovery: Macroscopic Displacement

- Vertical sweep efficiency

<table>
<thead>
<tr>
<th>Layer 1</th>
<th>Layer 2</th>
<th>Layer 3</th>
<th>Layer 4</th>
<th>Layer 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ (red)</td>
<td>Oil (green)</td>
<td>CO₂</td>
<td>Oil</td>
<td>Oil</td>
</tr>
</tbody>
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Scale: Feet
CO$_2$ Displacement Process

- Phase Behavior and PVT Properties
  - Liquid-like CO$_2$
  - Gas-like CO$_2$
- Immiscible/ Miscible Conditions
- Reservoir Pressure and Temperature
- Displacement Mechanisms
CO$_2$ Phase Behavior: Pressure Temperature Diagram

- Critical Temperature: 87.7 °F
- Critical pressure: 1073 psia

**Liquid or Gas**
(high density, low density)
CO$_2$ PVT Properties: Viscosity

- CO$_2$ Viscosity plot
- Greater Viscosity: lesser difference between oil and water density.
- Less viscosity difference leads to improved oil recovery
CO$_2$ PVT Properties: Density

- CO$_2$ Density plot
- Higher density; less difference between oil and water density.
- Less density difference leads to improved oil recovery

Fig. 8.33—CO$_2$ density (from Refs. 42 and 43).
Immiscible CO$_2$/Oil Mixture

- Temperature < 88 °F
  - pressure less than saturation pressure: gas
- Temperature > 88 °F & low Ppressure < MMP (Minimum Miscibility Pressure)

- Much less recent research for Immiscible CO$_2$
Miscible CO$_2$/Oil Mixture

- Temperature < 88 °F
  - pressure greater than saturation pressure: liquid
- Temperature > 88 °F & high pressure > MMP (Minimum Miscibility Pressure)
Displacement Mechanisms

- CO$_2$ is a solvent to crude oil
- CO$_2$ is used in core labs as a solvent to clean core of crude oil
- Displacement Conditions
  - Miscible
    - Multicontact
    - Miscibility Pressure
  - Immiscible
Displacement Mechanisms

- Multicontact Miscibility
  - Vaporizing/condensing process
  - Intermediate hydrocarbons from crude oil vaporize into the CO$_2$
  - CO$_2$/HC enriched gas becomes miscible with crude oil
Displacement Mechanisms

- Multicontact Miscibility

Low viscosity CO$_2$ moves through the crude oil vaporizing intermediate hydrocarbons. Eventually hydrocarbon enriched CO$_2$ becomes miscible with the crude oil.
Reservoir Mechanisms

• Positive Mechanisms
  – Oil viscosity reduction
  – Oil swelling
  – Oil surface tension reduction
  – Residual oil decrease
Reservoir Mechanisms

- **Negative Mechanisms**
  - \( \text{CO}_2 \) viscosity < Oil viscosity
    - \( \text{CO}_2 \) viscous fingers
  - \( \text{CO}_2 \) density < Oil density
    - Gravity override
Field Injection Options

- Continuous CO$_2$/Water Slug
- Water-Alternating-Gas (WAG)
Field Injection Options

- Continuous CO$_2$/Water Slug
Field Injection Options

• Continuous CO$_2$-Disadvantages
  – Early CO$_2$ breakthrough
    • Poor areal efficiency
    • Poor vertical efficiency
  – Large volume of CO$_2$
Field Injection Options

- Water-Alternating-Gas (WAG)
Field Injection Options

- WAG-Disadvantages
  - Water sensitive formations impaired
  - Water injection decreases with time
  - Operational: Corrosion (producing wells)
Field Injection Summary

• Methods designed to
  – Reduce CO$_2$ velocity
  – Increase macroscopic displacement efficiency
  – Reduce volume of CO$_2$ required/sequestered
Oil Reservoirs: Geologic Storage

- Compressibility (mixes with free gas phase).
- Soluble in crude oil
- Soluble in water (connate and/or waterflood water)
- Adsorption to some clay minerals
- Replacing oil and gas volume produced
Summary

- CO$_2$: gas-like viscosity, liquid-like density
- Liquid or critical CO$_2$ preferred for larger stored mass. (higher density)
- CO$_2$ is proven to increase oil production in oil producing basins where naturally occurring CO$_2$ reservoirs exist.
  - Miscible proven in the lab and field
  - Immiscible proven in the lab
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