Characterisation and use of polymer-gel solutions for CO$_2$ flow diversion and mobility control within storage sites

Sevket Durucan
Anna Korre, Rajesh Govindan, Mojgan Hadi Mosleh, Ji-Quan Shi
Imperial College London, United Kingdom
Outline

- Introduction and objectives
- Experimental programme
  - Characterisation of polymer-gel solutions
  - Core flooding experiments
- Numerical simulation of field polymer-gel injection scenarios: Flow diversion and/or leakage remediation
- Conclusions
Motivation and Objectives

Motivation

- Knowledge of geology and petrophysical properties of saline aquifers is limited, i.e. there is significant uncertainty in the verification of CO₂ flow conformance.
- A corrective actions plan describing the measures to be taken in the unlikely event of CO₂ leakage is an essential requirement of a CO₂ storage site license application.

Objectives

- To investigate the suitability of polymer-gel treatment to divert the flow of CO₂ and/or remediate leakage through
  - Laboratory characterisation of a number of polymer-gel solutions and their effectiveness in permeability control.
  - Numerical simulation of polymer-gel injection to assess their potential use for flow diversion or to remediate CO₂ leakage scenarios.
## Laboratory characterisation of polymer-gel solutions

### Polymer gel-systems tested

<table>
<thead>
<tr>
<th>Polymer type</th>
<th>AN1506</th>
<th>AN907PG</th>
<th>AO22</th>
<th>SB15</th>
<th>Xanthan</th>
<th>HPAM-LMW</th>
<th>PAM-HMW</th>
</tr>
</thead>
<tbody>
<tr>
<td>supplied by SNF Floerger, France</td>
<td>supplied by Sigma Aldrich, UK</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polymer type</td>
<td>Poly-acrylamide-based</td>
<td>Poly-acrylamide-based</td>
<td>Poly-acrylamide-based</td>
<td>Poly-acrylamide-based</td>
<td>Poly-saccharide</td>
<td>Poly-acrylamide-based</td>
<td>Poly-acrylamide-based</td>
</tr>
<tr>
<td>Molecular weight</td>
<td>High</td>
<td>High</td>
<td>Medium</td>
<td>Medium</td>
<td>High</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Form</td>
<td>Powder</td>
<td>Powder</td>
<td>Partially hydrolysed</td>
<td>Partially hydrolysed</td>
<td>Powder</td>
<td>Partially hydrolysed</td>
<td>Powder</td>
</tr>
<tr>
<td>Base solution</td>
<td>0.5%wt NaCl in deionised water</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>22 – 60 °C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crosslinker</td>
<td>Tyzor 217: water-based zirconium chelate (Zr⁺ content: 5.4%), supplied by SNF Floerger (Manufactured by Dorf Ketal)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Effect of polymer concentration on working times
- Effect of crosslinker concentration on working times
- Effect of temperature on working times
- Permeability reduction in core flooding experiments
AN1506, AN907PG and Xanthan were crosslinked by Zr\(^+\).

Gelation times at 2,500 ppm polymer concentration, 50 ppm Zr\(^+\) at 22 °C were:
- AN1506: ~1.5h
- AN907PG: ~28h
- Xanthan: ~480h (20 days)

AO22, SB15, HPAM-LMW and PAM-HMW did not produce gel even at much higher concentrations (up to 10%) and higher temperatures (up to 60°C).
Laboratory characterisation of polymer-gel solutions

Effect of polymer concentration on working times

- Faster gelation was observed at higher polymer concentrations.
- For polymer concentrations <500ppm, only partial gelation was observed and the produced gel was found to be weak and uneven.
Laboratory characterisation of polymer-gel solutions

Effect of crosslinker concentration on working times

- The ratio of polymer-to-crosslinker ($P/X$) was found to be important in determining the gelation and working times.
- Polymer solutions with $1<P/X<10$ did not undergo gelation, whereas those with $P/X>10$ were found to be more likely to undergo gelation.

![Diagram showing the effect of crosslinker concentration on working time]

$T = 22^\circ C$
Laboratory characterisation of polymer-gel solutions

Effect of temperature on working times

<table>
<thead>
<tr>
<th>Polymer type</th>
<th>Polymer concentration (ppm)</th>
<th>Zirconium concentration (ppm)</th>
<th>Working time (hr)</th>
<th>Gelation time (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AN1506</td>
<td>700</td>
<td>15</td>
<td>4</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>600</td>
<td>15</td>
<td>5</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>15</td>
<td>No gelation</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>1,500</td>
<td>15</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>1,200</td>
<td>15</td>
<td>No gelation</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>700</td>
<td>15</td>
<td>No gelation</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>2,500</td>
<td>50</td>
<td>22</td>
<td>24</td>
</tr>
<tr>
<td>Xanthan</td>
<td>700</td>
<td>15</td>
<td>1.3</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>15</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>15</td>
<td>No gelation</td>
<td>-</td>
</tr>
<tr>
<td>AN1506</td>
<td>2,500</td>
<td>50</td>
<td>0.08</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>1,000</td>
<td>15</td>
<td>0.3</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>15</td>
<td>1.5</td>
<td>partially gelled</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>15</td>
<td>No gelation</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>2,500</td>
<td>50</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>AN907PG</td>
<td>1,500</td>
<td>15</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>1,000</td>
<td>15</td>
<td>No gelation</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>15</td>
<td>No gelation</td>
<td>-</td>
</tr>
<tr>
<td>Xanthan</td>
<td>300</td>
<td>15</td>
<td>2.5</td>
<td>2.5</td>
</tr>
</tbody>
</table>

For higher concentrations of AN1506 and AN907PG, working time was significantly reduced with increase in temperature.
Polymer-gel core flooding experiments

Samples used: high permeability carbonate (Guiting) and sandstone (Doddington)

Procedure

- Samples saturated with brine (3%).
- Polymer gel injected into the core at constant rate (1mL/min).
- The system is isolated and polymer-gel in the pore space was left undisturbed to account for gelation time estimated from characterisation test.
- $\text{CO}_2$ was injected at constant pressure into the core sample to measure post-polymer injection $\text{CO}_2$ permeability and effectiveness of the polymer gel system.
Polymer gel-core flooding experiments

- A polymer-gel solution of 1,000ppm AN1506 and 15ppm Zr⁺ was used for the core flooding experiments, at 22°C.

- For Doddington sandstone:
  - CO₂ Permeability was reduced from 578mD to 0.03mD (99.99% reduction).

- For Guiting carbonate:
  - CO₂ permeability was reduced from 670mD to 1mD (99.85% reduction).
The effect of polymer to crosslinker ratio on gelation

- Numerical modelling using the chemical flooding simulator UTCHEM 9.0
- A simplified homogenous reservoir at ~1,600m depth, dipping at 22° was used to study gelation
- Simulation runs were performed for a range of polymer and crosslinker concentrations to assess the strength of gel formed and the area of influence.

- Concentration/strength of the gel formed increased with increased polymer and crosslinker concentrations
- At lower polymer to crosslinker ratios a relatively higher gel concentrations are achieved
- The area of influence decreases with increased polymer concentration
- Lower crosslinker concentrations yield a relatively higher area of influence
Numerical modelling of field polymer-gel injection

The saline aquifer model

- A generic reservoir model was set up to study the mobility control of CO₂ plume and leakage remediation using polymer-gel injection in a heterogeneous saline aquifer.
- The structural model used in the study has a broad and considerably dipping anticlinal structure.
- The model grid spans an area of 36km × 10km and includes five major sealing faults.

Reservoir:
- average thickness: 240m
- grid resolution: 200m × 200m × 4m

Caprock (seal):
- average thickness: 225m
- grid resolution: 200m × 200m × 225m

Shallow aquifer:
- average thickness: 175m
- grid resolution: 200m × 200m × 175m

The depth of the model ranges between -1,087m and -3,471m
The geological model

- The geological model represents a fluvial-channel system, typically containing braided sandstone channels and interbedded floodplain deposits (mudstone or siltstone).
- The petrophysical properties used in the model attribution are based on the Late Triassic Fruholmen Formation in the Hammerfest Basin, in the southern Barents Sea, located at depths similar to those considered in this study.
- The property attributions were generated using Sequential Gaussian Simulation (SGS) in order to represent the spatial uncertainty.
Model set-up and CO₂ injection

- A sub-seismic fault was introduced in the model at a distance of 1km away from the injection well, located at the flank of the anticline.
- A compositional flow model was setup in Eclipse 300 to simulate CO₂ injection at a rate of 1Mt/year.
- Leakage through the fault was detected inside the shallow aquifer after 1.75 years of CO₂ injection, considering 5,000 tonnes of mobile CO₂ as the lower limit for detection.
- CO₂ injection was temporarily terminated until polymer gel treatment in the reservoir was carried out.
- A number of scenarios were considered for the remediation of CO₂ leakage using low and higher viscosity polymer injection through horizontal well configurations.
- CO₂ leakage remediation was assessed during a total simulation period of 5 years.
**CO₂ leakage remediation results**

- The time period and amount of polymer-gel required to seal the leaky fault at the base of the caprock was assessed.

- After polymer-gel treatment, CO₂ injection was resumed for the remaining 5 year simulation period.

- Polymer-gel solution seals the fault and diverts the CO₂ flow as desired.

- Remediated and unremediated cases were for compared:
  - **Unremediated** case: the total amount of CO₂ loss from the reservoir without polymer treatment after the leakage was detected (160,000 tonnes).
  - **Remediated** case: the total amount of CO₂ loss until the start of polymer injection (80,000 or 100,000 tonnes for low and high viscosity polymer-gels respectively).
Conclusions

- Not all the polymers tested have gelled at simulated reservoir conditions.
- Laboratory characterisation work has indicated that as polymer type, molecular weight, polymer and/or crosslinker concentration, ratio of polymer-to-crosslinker and temperature has an effect on the gelation process and working time of the polymer-gel solutions tested.
- A reduction of more than 99% (2 - 4 orders of magnitude) was obtained in gas permeability at polymer concentrations of 1,000ppm, and Zr⁺ concentration of 15ppm in 0.5%wt NaCl.
- Numerical simulations have shown that the area of influence decreases with increased polymer concentration and lower crosslinker concentrations yield a relatively higher area of influence.
- Polymer-gel injection from a horizontal well close to the leaky fault can seal the caprock and remediate leakage.

*Note:* This is a shortened public version of a presentation made in Venice on 11 May 2016, further details can be found in recent and future publications by the Group.
Thank you very much for your attention!

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