Core Flood Modelling of Ion-Exchange during Low Salinity Waterflooding*

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Abstract

The present work contains a literature review of the key and latest publications on Low Salinity Waterflooding (LSWF) since its real development in the 1990s to explain the dominant mechanisms, numerical modelling processes and requirements to apply this Enhanced Oil Recovery (EOR) technique. To-date, there is no general agreement of the dominating mechanism that rules the LSWF effectiveness. Currently, wettability alteration to a more water-wet state of the rock as a result of ion exchange and/or double layer expansion mechanism are the two most feasible and supported pore scale mechanisms. However, most of the latest published numerical modeling methods aim to represent the wettability changes only because of Multi-Ion Exchange (MIE) processes and geochemical reactions. These publications crosscheck their results with observed laboratory data and with the chemical reactions obtained from a recognized geochemical simulator, PHREEQ-C (Kharaka et al., 1988).

The present project is oriented to reproduce experimental results obtained at Heriot Watt University with PHREEQ-C to investigate the effects of concentration changes of the low salinity injection brine on the ion-exchange reactions. Later the experimental results are reproduced using industry standard reservoir simulation software to reproduce the observed data in a 1D single-phase system. The reproduction of the experimental results will be used as basis to define correlations between grid size, cation exchange capacity (CEC), selectivity coefficients, and injection rates in a Multi-Ion Exchange modelling process and as a method to estimate the type of clay present in the system through the intrinsic CEC value. In addition, a 1D two-phase system is also the set up to observe the different oil recoveries as function of the injected pore volume when using different equivalent fractions and aqueous concentrations as relative permeability interpolants.

By using these models and a model that reproduce experimental data, a correlation between the CEC and the oil recovery factor is presented which can help to understand more the modeled MIE process.
Selected References


Core Flood Modelling of Ion-Exchange during Low Salinity Waterflooding

- Nestor Vásconez (Schlumberger),
- Yerulan Sabyrgali, Eric Mackay (Heriot-Watt University)
LOW SALINITY WATER INJECTION

OBJECTIVES

- Reproduce experimental data using Geochemical & Reservoir Simulation software in a 1D single phase system
- Perform LSW in a two phase system using the matched core characteristics
- Gain more insight into modelling LSW
LOW SALINITY WATER INJECTION MECHANISMS

- Different mechanisms are responsible for Low Salinity Water Efficiency:
  - Electrical Double Layer Expansion
  - Multi-Ion Exchange
  - Fines Migration
  - pH increase and more
  - After 24 years: no general agreement among researchers
LOW SALINITY WATER INJECTION

MECHANISMS

Electrical Double Layer Expansion

Resulting effect:
• Change in wettability
• Facilitates oil removal
• Supported by experimental observations
• Considered an effect not a mechanisms

(Aladasami et al., 2014)
LOW SALINITY WATER INJECTION MECHANISMS

Multi-Ion Exchange

- Observed at core and field scale
- However, polar oil components can adsorb onto clay minerals without a bridge.

These 2 mechanisms change the wettability towards a more water wet system.
LOW SALINITY WATER INJECTION

Modelling LSW

• Single phase data can be represented using a well-known Geochemical simulator

• Modelling LSW is limited in current reservoir simulators to Relative Permeability Interpolation from HS Kr to LS Kr using brine tracking.

• A compositional numerical simulator with Geochemical processes is used.

• Identify a tool for modelling LSW comparing the results with observed experimental data.
MATCHED EXPERIMENTAL DATA USING PHREEQ-C:

1D GEOCHEMICAL SIMULATOR

PHREEQ-C VS EXPERIMENTAL DATA
(Heriot Watt University)

<table>
<thead>
<tr>
<th>Brine / Ions (ppm)</th>
<th>Na$^+$</th>
<th>Ca$^{2+}$</th>
<th>Mg$^{2+}$</th>
<th>K$^+$</th>
<th>Cl$^-$</th>
<th>TDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formation</td>
<td>22000</td>
<td>238</td>
<td>90</td>
<td>230</td>
<td>35500</td>
<td>~58058</td>
</tr>
<tr>
<td>Injection</td>
<td>588</td>
<td>14</td>
<td>1.75</td>
<td>19</td>
<td>941</td>
<td>~1563</td>
</tr>
</tbody>
</table>
# MODELLING LOW SALINITY WATER AT CORE SCALE

<table>
<thead>
<tr>
<th>MODEL</th>
<th>1D MODEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>CELLS</td>
<td>10 – 20 - 40 CELLS</td>
</tr>
<tr>
<td>SIMULATOR</td>
<td>GEM</td>
</tr>
<tr>
<td>PROCESS MODELED</td>
<td>ION EXCHANGE</td>
</tr>
<tr>
<td>DATA INPUT</td>
<td></td>
</tr>
<tr>
<td>ION CONCENTRATION</td>
<td>FROM EXPERIMENTAL DATA</td>
</tr>
<tr>
<td>FORMATION BRINE</td>
<td></td>
</tr>
<tr>
<td>INJECTION BRINE</td>
<td></td>
</tr>
<tr>
<td>EFFLUENT CONCENTRATION</td>
<td></td>
</tr>
<tr>
<td>PHREEQC</td>
<td>1D GEOCHEMICAL SIMULATOR</td>
</tr>
</tbody>
</table>

![Graph showing 3D Reservoir study](image)
MATCHING EXPERIMENTAL DATA USING GEM:

\[ Na^+ + 0.5(Ca - X_2) \leftrightarrow (Na - X) + 0.5Ca^{2+} \]  \hspace{1cm} (1) \hspace{1cm} \text{S.C. 0.4}

\[ Na^+ + 0.5(Mg - X_2) \leftrightarrow (Na - X) + 0.5Mg^{2+} \]  \hspace{1cm} (2) \hspace{1cm} \text{S.C. 0.4}

\[ Na^+ + (K - X) \leftrightarrow (Na - X) + K^+ \]  \hspace{1cm} (3) \hspace{1cm} \text{S.C. 0.1}

Cation Exchange Capacity:
350 meq/L

3.09 meq/(100 grams of rock)

Kaolinite range
MATCHING EXPERIMENTAL DATA USING GEM:

IMPROVEMENT OVER PHREEQ-C IN MODELLING ION-EXCHANGE
MATCHING EXPERIMENTAL DATA USING GEM:

SENSITIVITIES TO THE GRID RESOLUTION: 20 to 10 CELLS

GEM VS EXPERIMENTAL DATA
GRID RESOLUTION: 10 CELLS CEC 175 - 20 CELLS CEC 350
Injection Rate: 3 cc/hr

- Ca+ Lab
- Ca++ 10 CELLS - CEC 175 STCH 0.12
- Ca++ 20 CELLS - CEC 350 STCH 0.12
- K+ Lab
- K+ 10 CELLS - GEM CEC 175 STCH 0.12
- K+ 20 CELLS - GEM CEC 350 STCH 0.12
- Mg++ Lab
- Mg++ 10 CELLS - GEM CEC 175 STCH 0.12
- Mg++ 20 CELLS - GEM CEC 350 STCH 0.12
- Na+ Lab
- Na+ 10 CELLS - GEM CEC 175 STCH 0.12
- Na+ 20 CELLS - GEM CEC 350 STCH 0.12
MATCHING EXPERIMENTAL DATA USING GEM:

SENSITIVITIES TO THE GRID RESOLUTION: 40 to 20 CELLS

GEM VS EXPERIMENTAL DATA
GRID RESOLUTION 20 CELLS CEC 350 - 40 CELLS CEC 700
Injection Rate: 1.5 cc/h

- Ca++ Lab
- Ca++ 20 CELLS - CEC 350 STCH 0.12
- Ca++ 40 CELLS - CEC 700 STCH 0.12
- K+ Lab
- K+ 20 CELLS - GEM CEC 350 STCH 0.12
- K+ 40 CELLS - CEC 700 STCH 0.12
- Mg++ Lab
- Mg++ 20 CELLS - GEM CEC 350 STCH 0.12
- Mg++ 40 CELLS - CEC 700 STCH 0.12
- Na+ Lab
- Na+ 20 CELLS - GEM CEC 350 STCH 0.12
- Na+ 40 CELLS - CEC 700 STCH 0.12
LOW SALINITY WATER INJECTION: TWO PHASES

Relative Permeability Interpolants:
1. Equivalent Fraction
2. Aqueous concentration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>PSIa</td>
<td>4500</td>
</tr>
<tr>
<td>Temperature</td>
<td>F</td>
<td>160</td>
</tr>
<tr>
<td>Viscosity @ 4500 PSIa</td>
<td>cP</td>
<td>0.42</td>
</tr>
<tr>
<td>Volumetric oil factor @ 4500 PSIa</td>
<td>Ad</td>
<td>1.17</td>
</tr>
<tr>
<td>Density</td>
<td>lb/cu.ft</td>
<td>45</td>
</tr>
</tbody>
</table>

Oil Composition

- C1: 0.2
- C4: 0.2
- C10+: 0.6

HS & LS RELATIVE PERMEABILITY CURVES

- HSKro
- LSKro
- HSKrw
- LSKrw

Distinctly Innovative
www.hw.ac.uk
LOW SALINITY WATER INJECTION:
TWO PHASES

1. Interpolant: Equivalent Fraction

![Graph showing oil recovery factor vs. injected pore volume with K+ and Mg++ sensitivities. The graph includes curves for different ions and a dashed line for high salinity waterflooding.]
LOW SALINITY WATER INJECTION: TWO PHASES

Interpolant: Equivalent Fraction

Up to 70 PV to reach equilibrium

![Graph showing the sensitivity of K+ and Mg++ to oil recovery factor and HSWF with respect to injected pore volume.](image)
LOW SALINITY WATER INJECTION: TWO PHASES

2. Interpolant: Aqueous concentration

Early LSW effect

0 - 50.0 PV

0 - 5.0 PV
LOW SALINITY WATER INJECTION: TWO PHASES

Interpolant: Aqueous concentration vs Equivalent Fraction

![Graph showing molality vs equivalent fraction](image)
LOW SALINITY WATER INJECTION: TWO PHASES

CEC effect on Oil Recovery: matched model by Dang (2013)
LOW SALINITY WATER INJECTION: TWO PHASES

Brine Optimization

Reduction of the Ion Concentration

Figure: 1D SIMULATION MODEL INJECTION BRINE OPTIMIZATION

- Decrease in $Mg^{2+}$ conc.
- Increase in oil recovery

Formula: Injected Pore Volume Mg
LOW SALINITY WATER INJECTION: TWO PHASES

Brine Optimization: 5-10 times reduction in Ion Conc.
CONCLUSIONS

• Single phase LSW can be reproduced using a 1D Geochemical simulator

• A general scaling factor to modify the CEC of the rock is presented as well as the parameters that do not interfere in the Ion-Exchange process.

• A general dependence of the rock CEC against oil recovery was found supported by a published simulation model based on experimental data.

• The sensitivities on the equivalent fraction of different ions as interpolants result in important ranges of recovery with different amounts of PV needed to reach new equilibrium conditions.

• Economical considerations are vital when deciding to implement a LSW as many pore volumes may be needed before observing a successful EOR.

• The brine optimization process performed in the current report agrees with experimental observations and requirements for LSWE.
RECOMMENDATIONS

• Inclusion of mineral reactions together with the Ion-Exchange model in order to identify the sustained behaviour of K.

• Reproduce observations that mention MIE as secondary mechanism.

• The inclusion of Kaolinite which is present in most of the reported observations is highly recommended as well as the analysis of additional variables such as pH, which can locally contribute to an increase in oil recovery at core scale.

• The inclusion of the PHREEQ-C code in open code standard reservoir simulators could lead to an important advance in terms of EOR modelling as reported in literature (Korrani et al., 2013, Korrani et al., 2014)
THANK YOU!